ANALYSES AND TRADE OFFS
SUPPORTING THE SDI SYSTEM ARCHITECTURE
(PHASE 2C PROGRAM)

MOTOROLA INC.
Government Electronics Group

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ANALYSES AND TRADE OFFS

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(PHASE 2C PROGRAM)

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FINAL REPORT

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FORWARD

This report summarizes, and in certain areas extends, the analyses and key tradeoff studies the Strategic Electronics Division of the Government Electronics Group of Motorola, Incorporated has performed for SPARTA, Incorporated, from March 1987 to January 1988 on Subcontract No.87-094 in support of SPARTA's Systems Security tasking on their Phase IIC contract (MDA 903-85-C-0064) for the SDI Systems Security and Key Technologies Program.

The areas covered during this period included the following preliminary reports generated by Motorola for SPARTA: 1) a jamming estimate (Secret report, entitled "Threat Technology," dated July 20, 1987); 2) a preliminary assessment of transmission and antenna technology; anti-jam and coding techniques; system security, processors, COMSEC/TRANSEC, authentication, and IC device technologies (report, entitled "Technology Preliminary Assessment Report," dated 19 May 1987); and, 3) three white papers, "Trends in Radiation Hardened Micro-Electronics for SDI," "Embedded Comsec for SDI," and "Impact of Compusec on Fault Tolerant Computers" (report, entitled "SDI Technology Assessment Report," dated 21 May 1987). Though portions of this final report are drawn from these previously submitted reports and some reference is made to them, they are not extended here, per se, and therefore stand alone in their original form. Appendices C, D, and E are exact reproductions of the three white papers.

Nevertheless, another jamming scenario is incorporated here that follows specifically from the more current October 1987 World Situation Set, Appendix A, rather than the earlier Secret work. Appendix B contains information on the propagation of EHF waves through a nuclearly-perturbed environment that was informally presented during discussions with SPARTA at Motorola on November 9-10, 1987.

A series of charts, curves, and block diagrams, with an appropriate amount of supporting text (report, entitled "Anti-Jam Communication System Design," undated--hand delivered to SPARTA on August 26, 1987) depicts a general communications system design for SDI satellites. Spread-spectrum techniques are inherent in that work and in the work presented here. We conclude that pseudo-noise (PN) spreading should be employed to the extent where nuclear scintillations have a relatively limited adverse effect (further discussion in Section II). The remainder of the available bandwidth should then be used for frequency hopping. The geometry itself will counter any potential follower-jamming threat provided that pulse widths are kept reasonably short--a microsecond is recommended, but it can be wider (see Section II). The state-of-the-art does not need to be improved in any of these areas. Section II provides additional jamming information which is then used in the margin analysis of Section VI.

A collection of charts and a presentation entitled "SDI Laser/EHF Communications Link Comparison" was presented at SPARTA in both August and October 1987 as an interim look at the subject and as a departure point to elicit feedback. A Technology Preliminary Assessment Report (entitled "Communications Architecture Consideration," dated 3 December 1987) developed the topic further and expanded the analysis into a more global context. While the early work focused more on key technical areas, the later work gave more emphasis to an overall architectural concept.

This final report is structured more globally, similar to the latter report, folding in or referring to the earlier work as appropriate and completing the analyses alluded to in the 3 December report. Continued analysis, beyond the scope and resources of this effort, is needed to hone the details of the concept developed; nevertheless, this provides, at least in part, a sound and systematic technological basis for policy decisions and a general systems baseline.

In both content and emphasis, EHF communications links will appear to overshadow lasercom links in this report. Though originally unanticipated, the evolution toward EHF communications occurred quite logically. Considerable emphasis has been given to lasercom by various advocacy groups and a "systematized" conceptual laser approach for several of the links was described in earlier work done for the SDIO, some through RADC. In this

comparison of EHF with laser technology for the SDI links, no comparable systemization of EHF (choosing architectural tradeoffs better supporting EHF) for SDI links could be found. Therefore, one was developed here for comparison purposes.

On the other hand, when seeking information to characterize and to size both EHF and lasercom systems, we found the EHF information readily available from people building space-qualified hardware, whereas lasercom information was largely conjectural--space-qualified laser hardware was of a different type and not easily transferrable into the SDI context, and that hardware of relevance is still primarily in the laboratory, not yet developed into a space-based configuration. This represents a case in point for what is one of the primary differences between lasers and EHF: technical maturity. The EHF architecture proposed here requires some limited further development, primarily in the area of electronically steerable antennas, but this development is relatively low risk as known steps are taken to completed the design. Lasers, on the other hand, require technical breakthroughs in several largely undefined areas that may or may not be completed in time for SDI.

Perhaps one of the more succinct observations is that lasers offer considerable promise in AJ, prime power, bandwidth, etc. and EHF should be thought of as the SDI baseline position; nevertheless, if laser research is well supported and EHF research is not, and if laser research fails to develop or

develops too slowly, when it comes time to launch the SDS, no communications may be available. Both technologies must continue to be supported.

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I. INTRODUCTION

INTRODUCTION

The overall security architecture for the Space Defense Initiative (SDI) has as its fundamental backbone the communications architecture for the Space Defense System (SDS). Communications among the various space segments, airborne nodes and ground nodes (as currently postulated for SDS) must be designed to maintain connectivity in the presence of hostile interference from electromagnetic (EM) jammers, in the case where EM communications links are used, or electro optic (EO) or infrared (IR) jammers, in the case where laser communications links are used, as well as from nuclear scintillations generated by localized (probably exoatmospheric) events purposefully focused on SDS communications links. Furthermore, Communications Security (COMSEC), Transmission Security (TRANSEC), and Computer Security (COMPUSEC) must be maintained at appropriate levels to guarantee that military operating concepts, strategies, and tactics are not compromised during the normal peacetime functioning of the SDS and during military exercises. It is expected that SDS will require layers of security and compartmenting of information. Specific security topics are addressed in Section VIII and in the Appendices.

The focus of the analysis in this report is narrowed in two ways: 1) Connectivity of the SDS is the primary topic, and 2) Connectivity among and within the SDS satellite constellations is treated most heavily.

Though the SDI/SDS Baseline Concept Definition (BCD) was used as a departure point, it was treated as advisory, not as directive, in nature. As such, an architecture for a very robust SDS netting of nodes is proposed here which can carry data at rates ranging from a few kilohertz (KHz) to hundreds of megahertz (MHz). Such a network will degrade very gracefully whether jamming or scintillation degrades links or whether nodes are actually lost.

The postulation of the communications system described in the pages that follow actually evolved heuristically rather than by design. In searching for the relative merits of using lasercom links versus extremely high frequency (EHF) links (30 to 300 gigahertz (GHz)) it appeared that many BCD parameters did not allow for exploiting some of the EHF option's greatest advantage, most notably the ability to support many narrow beam links by employing electronically-agile, multi-beam antennas. When parallel links and the relay of information among the satellites are reconsidered, a very robust architecture is possible. Now it appears that lasers may also, at some point in time, be able to slew over a wide range very quickly, so robustness may not totally be dependent on EHF; although for now, the steps needed to support a very robust EHF architecture are understood and achievable, whereas a comparably robust laser architecture involves risky unknowns. A comparison of lasers versus EHF is included in Section X, while the size, weight, and prime power

requirements for EHF are treated in precise detail in Section IX and the comparable laser information is still subject to much conjecture and thus treated more generally in that same section.

Jamming threats can be of several types and one of the fundamental postulates to consider is that one does not get into a power against power situation with the adversary enjoying static ground resources while trying to counter him from a mobile (especially airborne or spaceborne) platform. As such, virtually all space-to-space EHF links are focusing in the atmospheric absorption regions near 60 GHz. (While there are similar regions at 118 GHz and 180 GHz, current technology more readily supports a 60 GHz baseline.) Jamming techniques and a postulated threat from the World Situation Set (Appendix A) are discussed in Section II, and these numbers, together with the nuclear scintillation numbers from Appendix B, are used in an overall margin analysis described in Section VI.

The robust architecture presented herein is derived from the SDS geometry depicted in Section III, and the numbers of parallel links and data rates are described in Section IV. A discussion of antenna systems to support this architecture is contained in Section V, and a numerical analysis, as well as a qualitative analysis, of the value of these parallel connectivity links is shown in Section VII.

In total this report describes a secure communications architecture for SDI/SDS with a discussion of relative advantages/disadvantages of laser versus EHF communications systems. EHF communications currently enjoys the major advantage of being more technically mature and, with the exception of one major technical thrust, in the area of electronically-agile antennas, the current state-of-the-art is not pushed beyond known developmental steps. On the other hand, any of the several laser sources, and each of their unique wavelengths, requires significant development, not the least of which is the packaging for sustained operations in space.

II. THREAT

THREAT

A summary of potential jamming threats is shown in Table II-1. Each of the generic threats will be discussed here briefly.

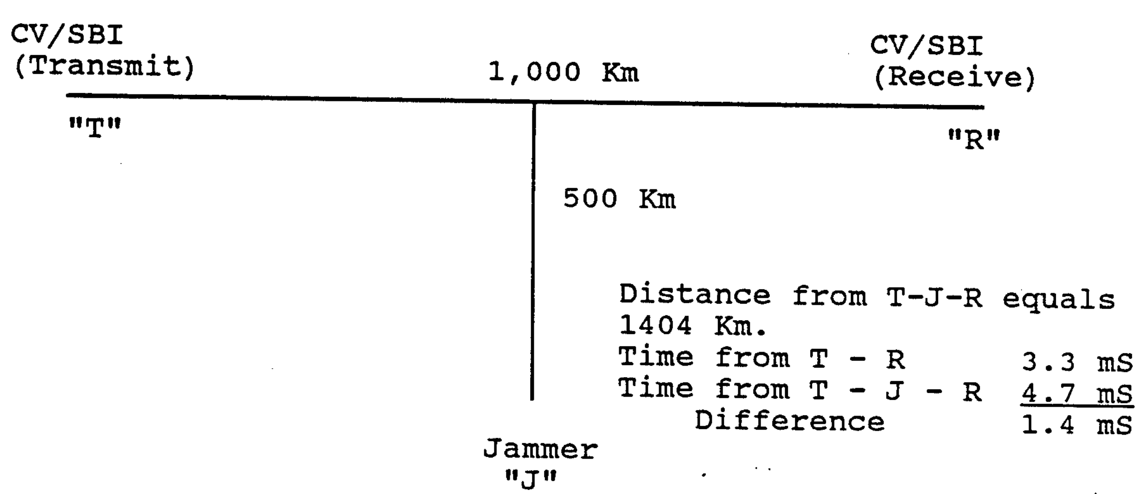
Follower Jammer. The usual design requirements to negate the potential effects of a frequency follower can be relaxed even further for the SDI/SDS. The geometry itself will counter such a threat since the distances between satellites are so great and any orientation that takes a potential jammer off the straight line between satellites adds to the permissible dwell time.

Consider the simple case where two CV/SBIs are 1000 Km apart. If a follower jammer is off as little as 500 Km from the mid-point between the two satellites the added distance adds more than a millisecond delay to the Transmitter-Receiver routing (See Figure II-1) and the jamming signal misses the receiver if the dwell time is a millisecond or less!

Table II-1. SUMMARY JAMMING THREATS

JAM THREAT	USUAL DESIGN REQUIREMENTS	STATE OF ART
Follower Jammer	100ns Dwell Time	10nS Dwell Time 32 Freq Cells
Tone Jammer	Direct Sequence PN	1 GHz/S
High Power Broad Band Jamming	Spread Bandwidth	4 GHz
	Null Steering	20 dB Null
Pulse Jammer	Data Interleaving	Long Memory Error Correcting Coding

Figure II-1



Generally it is assumed that <u>half</u> of the signal dwell must be overwhelmed by a follower's power to deny connectivity; therefore, a dwell time as wide as 1 uS would require a transmit-jammer-receiver routing to stay within 150 m of the transmit-receive line-of-sight (LOS) to be effective! Given the distance involved, the fact that all satellites are always moving, and the fact that satellites at different radii move at different rates, it is inconceivable that a sufficient number of follower constellations can be launched against the SDS unless one jammer is devoted to each SDS satellite (positioned in the same orbit of each SDS satellite, going in the same direction, within 150 m LOS). The SDS postulates a 500 Km minimum spacing (kill distance), so effective follower jammers are simply not a threat.

A nominal 1 uS dwell time is therefore assumed as a baseline parameter for the EHF system presented here.

<u>Tone Jammer</u>. Direct sequence PN spreading up to 1 GHz is within the state-of-the-art to protect against enemy tone jammers. For the SDS, however, a stricter limit on PN spreading (between 10 MHz and 100 MHz) occurs due to the propagation limitations associated with exoatmospheric nuclear events (See Appendix B). Depending upon the link, the PN spreading is selected to be between 10 MHz and 100 MHz.

High Power Broad-Band Jammer. Spread Spectrum is a key element negating the effect of high power. It is assumed here that the full advantage of the available bandwidth (10%) will be used. As a baseline, once the PN-spreading is selected, the total available bandwidth is divided into hopping frequencies, and a 1 uS dwell time (from above) will employ a 100% duty-factor yielding a 1 MHz hopping rate.

Null steering should be considered on a link to link basis and as many as two nulls should be available per beam; 20 dB of added margin is within current technology.

Route diversity and parallel links, coupled with the previous and following methods, can pretty much guarantee connectivity against any jamming threat. The geometry of a very robust system is described in the next section.

Pulse Jammer. Long-memory error detecting and correcting codes (EDACs) are within current capabilities. As a baseline, data interleaving, and even synchronization-bit interleaving, is a preferred approach.

Summary. Given an architecture employing the parameters described above and coupled with the geometry and parallel links defined in the next sections, even a perfunctory jamming threat deployed by an adversary would be an obviously poor use of their resources. Their threat to deploy, however, does have great

value since it forces us to add significant complexity, and expense, to our system. The threat to SDS would then have to come from sources other than jamming. Nevertheless, the WSS postulates 36 jammers and they are positioned here for apparently maximum effectiveness.

The threats of concern to the design of the communication links are the EW and nuclear threats. The EW threat is based on the use of airborne and space jammers whose nominal characteristics are given in Table II-2 and II-3. It is assumed that each receiver is equipped with error correcting codes, interleaving, and a hybrid frequency hopping/direct sequence spread spectrum system so that the optimum jammer strategy is to resort to broadband noise jamming. Hence the importance of the bandwidth parameter shown in the tables below.

Per the WSS, the airborne jammer is assumed capable of transmitting 200 KW of power and utilizes a 3 meter antenna at 50% efficiency. The airborne jammer parameters are summarized in Table II-2.

The space-based jammers are capable of 5.2 KW of output power and are assumed to be equipped with monolithic array antennas capable of producing multiple independently steerable beams. The parameters of the space based jammers are summarized in Table II-4.

TABLE II-2
AIRBORNE JAMMERS

Frequency GHz	Power dBm	Antenna Gain (dB)	EIRP dBm	Bandwidth GHz
20	83	53	136	2

TABLE II-3
SPACE BASED JAMMERS

Frequency GHz	Max Power dBm	Antenna Gain (dB)	Max EIRP (dBm)	Bandwidth GHz
20	67.2	60	127.2	2
44	67.2	55	122.2	4.4
60	67.2	50	117.2	6.0

TABLE II-4
DNA MULTIPLE BURST ENVIRONMENT

	30 GHz	60 GHz
To	.04 msec.	.08 msec.
fo	2.6 MHz	41 MHz
Scattering Loss	21.2 dB	15.1 dB
Absorption	4.8 dB	1.1 dB
Ant. Temperature	8900° K	4000° K

The space-based jammers are divided into 2 constellations. One constellation consists of 6 jammers in the same orbit as the BSTS satellites and spaced a distance of 1,000 Km from each of the BSTS satellites. The remaining 30 jammers are uniformally distributed in the SSTS planes, at an altitude midway between the SSTS and CV/SBI constellations. These jammers are assumed to be equipped with multiple-beam phased-array antennas so that a single jammer can jam 2 SSTS satellites and 10 CV/SBI satellites simultaneously. Assuming 5.2 KW of available power, 1,737 W have been allocated per SSTS satellite and 173.6 W per CV/SBI all at 60 GHz.

The nuclear threat is based on 60 bursts uniformly distributed over a 2,000 Km x 3,000 Km region at an altitude of 250 Km. Table II-4 shows the resulting significant parameters to be used in the Rayleigh fading model proposed by DNA at 30 GHz and 60 GHz. These nominal parameters are used in computing the various link margins discussed in Section VI. A further discussion of the nuclear fading model can be found in Appendix B.

III. REPRESENTATIVE GEOMETRY

REPRESENTATIVE GEOMETRY

INTRODUCTION

With the most current information available, nominal constellations for the BSTS, SSTS, and CV/SBI satellites are formed to depict the robustness in angular diversity of the communications links. All LOS links at least 100 Km above the earth's surface are considered. A primary thesis is that the robustness of the geometry provides an inherent degree of protection against both electronic countermeasures (ECM) and natural phenomena. To disregard the advantages inherent in such a robust geometry is tantamount to giving adversaries constellations of jammers which render these potential links useless. The depictions shown here of the angular diversity also aid in determining antenna system designs that should be considered for each type of satellite.

Angular diversity coupled with parallel links provide advantages to the overall SDS beyond that associated with possible ECM and natural phenomena. First, regardless of how/why a link or a mode breaks down, degradation of the entire system is considerably more graceful than one in which a relatively static architecture is employed. Secondly, whenever a nuclear event occurs, disruption of communications for any particular satellite can be expected in that general radial region from the satellite toward the event, whereas links in other directions may very well (depending upon the proximity of the event) maintain their

connectivity. Thirdly, the overall link margin and bit-error rate (BER) is improved.

The geometric diversity is primarily explained here in a pictorial form. The data rates, number of links, margin analysis, etc. follow in later sections.

All plots are static determinations of available lines of sight. No attempt is made to calculate links at all points in all orbits, but rather to calculate links available for representative geometries. Constellations are generated for each satellite type: BSTS, SSTS, and CV/SBI.

Several simplifying assumptions are made. The BSTS satellites are all put in the equatorial plane. From orbit to orbit the CV/SBI satellites are not offset from one another; however, the SSTS satellites are equally offset in phase from orbit to orbit. Orbital planes are uniformly distributed within constellations. And, all satellites within a constellation are in circular orbits with identical radii, and the radii are representative of the current expectation of orbital parameters.

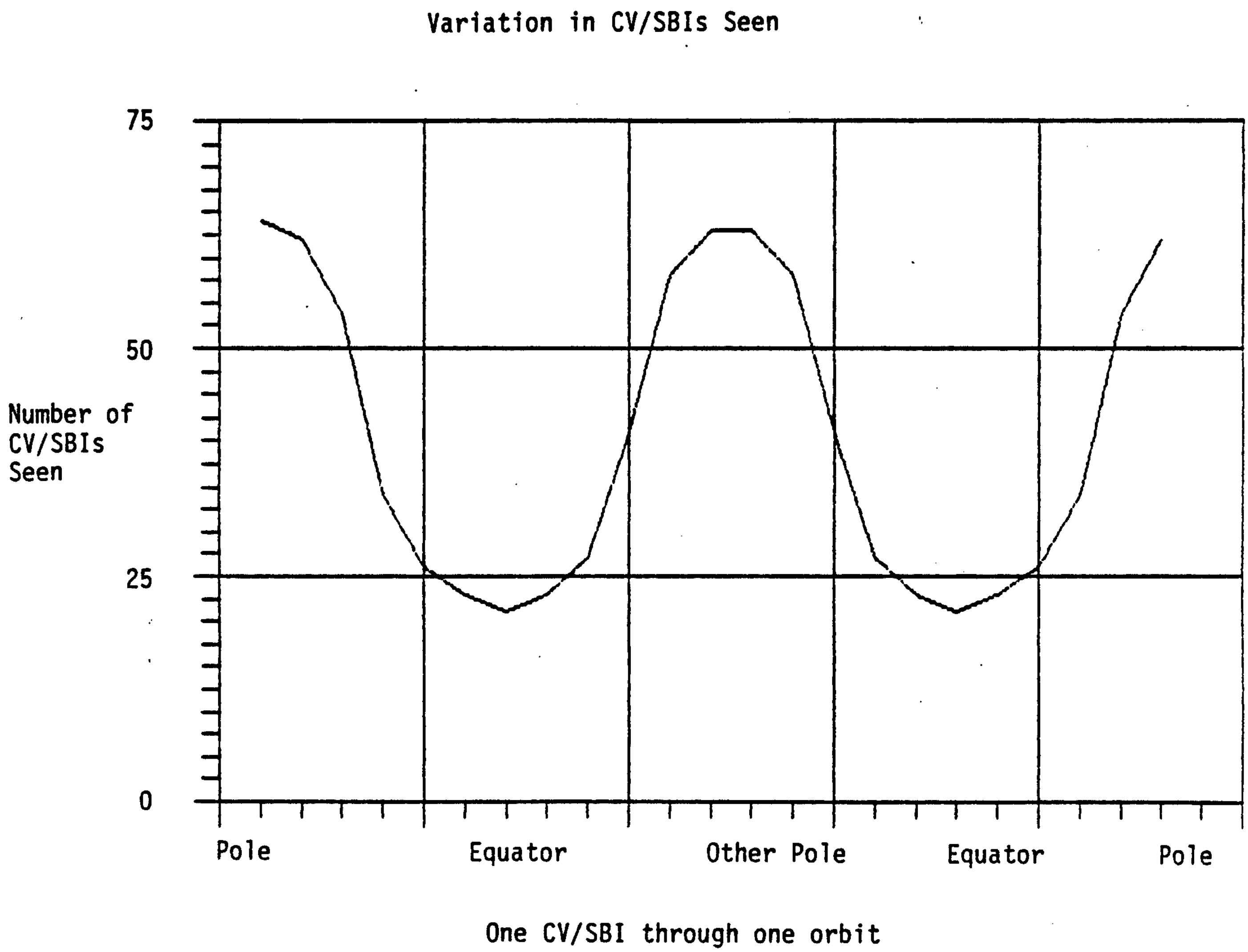
Nevertheless, the enclosed analysis is most representative of the robustness of the geometry available for communications.

CV/SBI - CV/SBI LINKS

Figure III-1 represents the number of CV/SBI satellites that can be seen from any one CV/SBI satellite. At the higher latitudes (both north and south) more than 60 are visible, whereas at the equator, just under 25 can be seen.

Though the current philosophy precludes these satellites from performing communications relay functions, maintaining a nominal number of (10) links per CV/SBI adds significantly to both the BER and to the relative immunity to jamming. Further study on the value of multiple links is included in Section VII.

FIGURE III-1



Variation in CV/SBIs Seen
75
50
25
0
Number of CV/SBIs Seen
Pole
Equator
Other Pole
Equator
Pole
One CV/SBI through one orbit

Figures III-2, 3, and 4 depict the look angle diversity available among the CV/SBI-to-CV/SBI links from a CV/SBI satellite positioned at a very high latitude (near the North Pole).

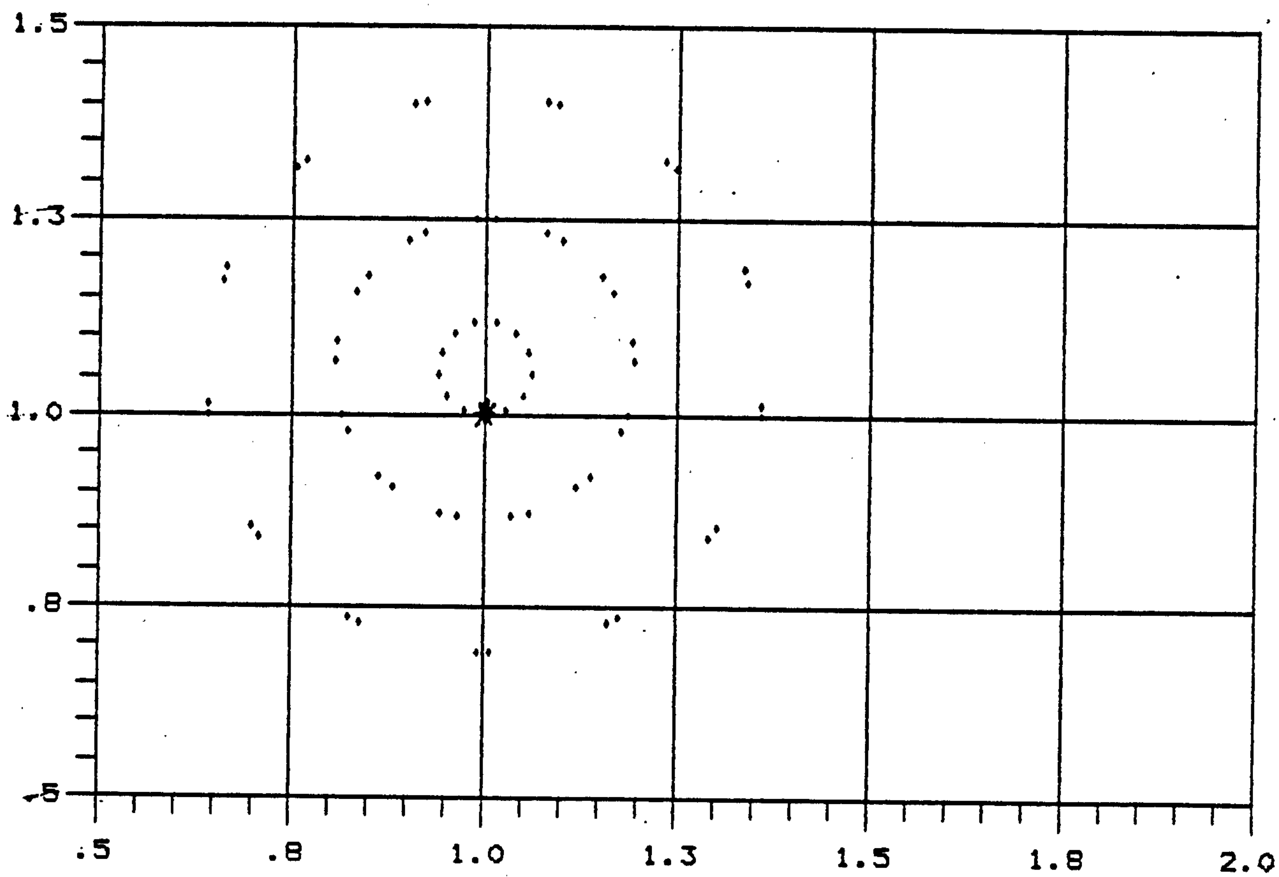
Figure III-2 shows the angular diversity as seen from a point along a line from the center of the earth through the CV/SBI satellite at a very large distance. The satellites are distributed unequally, but not bunched, around 360^o. This view will be referred to as the back view. Note that for all back, side, and top views, the abscissa and ordinate have equal scales; therefore, all angles are true. In some cases a dot or X can represent more than one satellite.

Figure III-3 shows the same geometry as viewed from the side. (Assume side means "at a great distance on the right normal line from the CV/SBI parallel to a plane of latitude.") In this case, many of the dots represent two satellites. In this case, the satellites are unequally distributed around approximately 180^o and some angular bunching is apparent.

Figure III-4 shows the same geometry as the previous two but viewed from the top. (Assume top means "at a great distance on the top normal line from the CV/SBI parallel to a plan of longitude including the center of the earth and the CV/SBI satellite.") Here, again, the satellites are equally distributed around approximately 180^o with some angular bunching.

FIGURE III-2

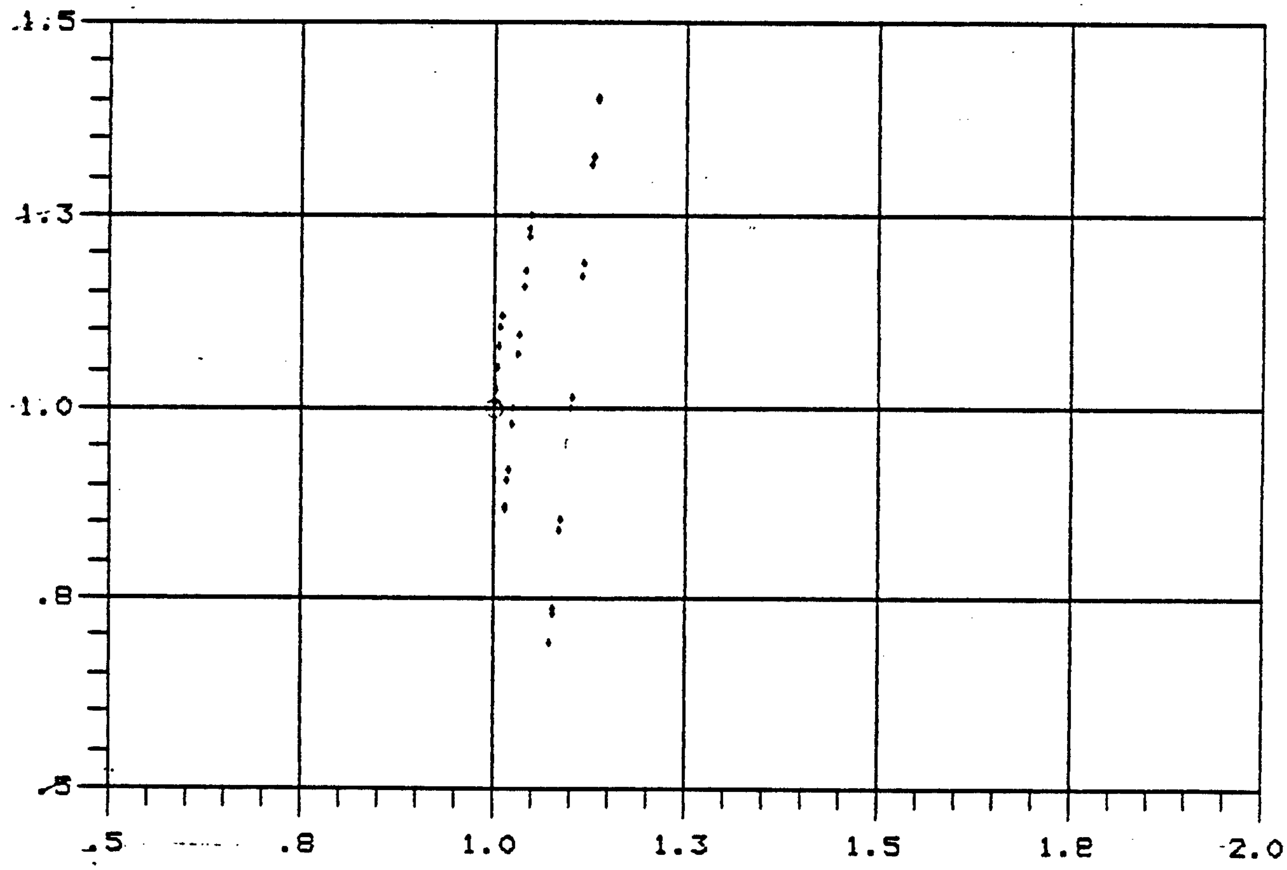
Back View (CV/SBI to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM

FIGURE III-3

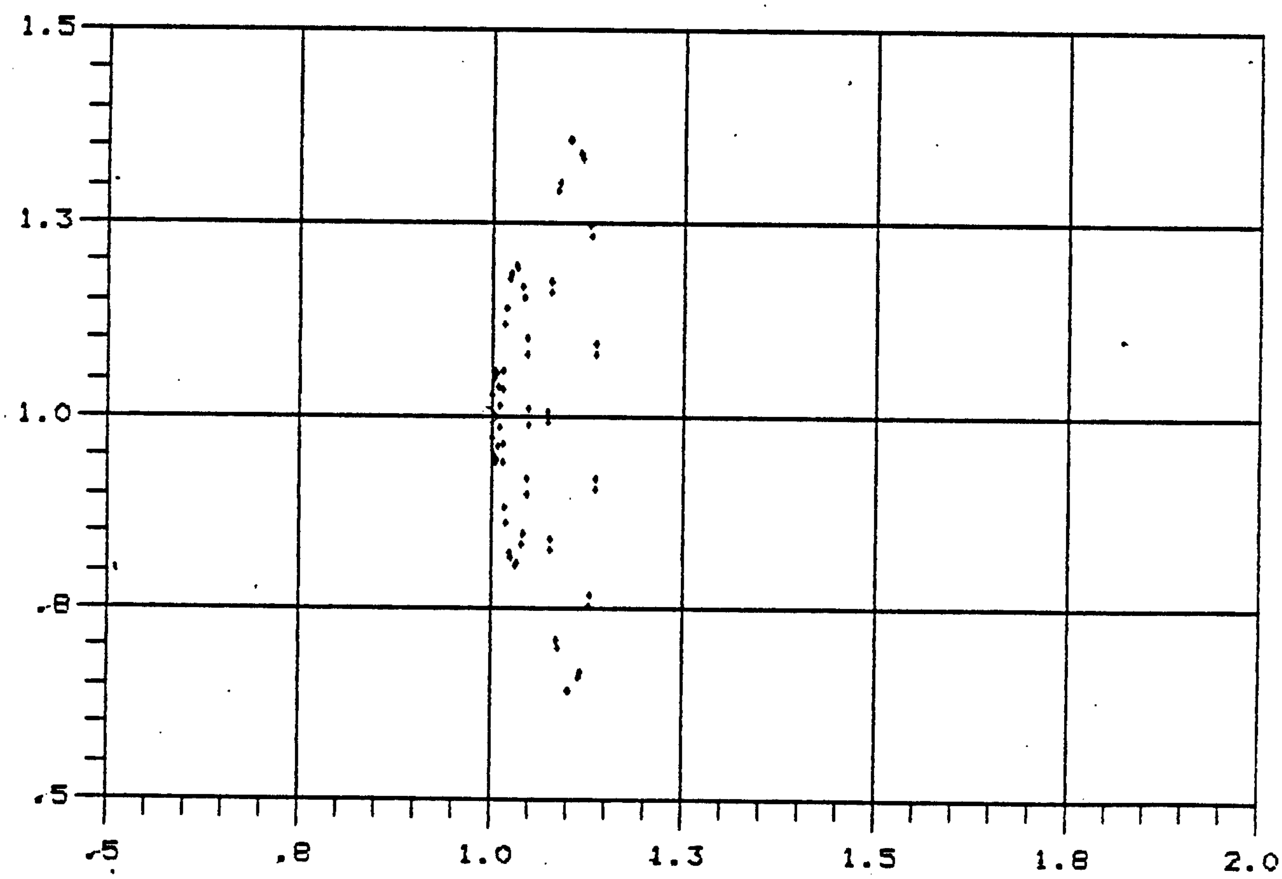
Side View (CV/SBI to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM

FIGURE III-4

Top View (CV/SBI to CV/SBIs)



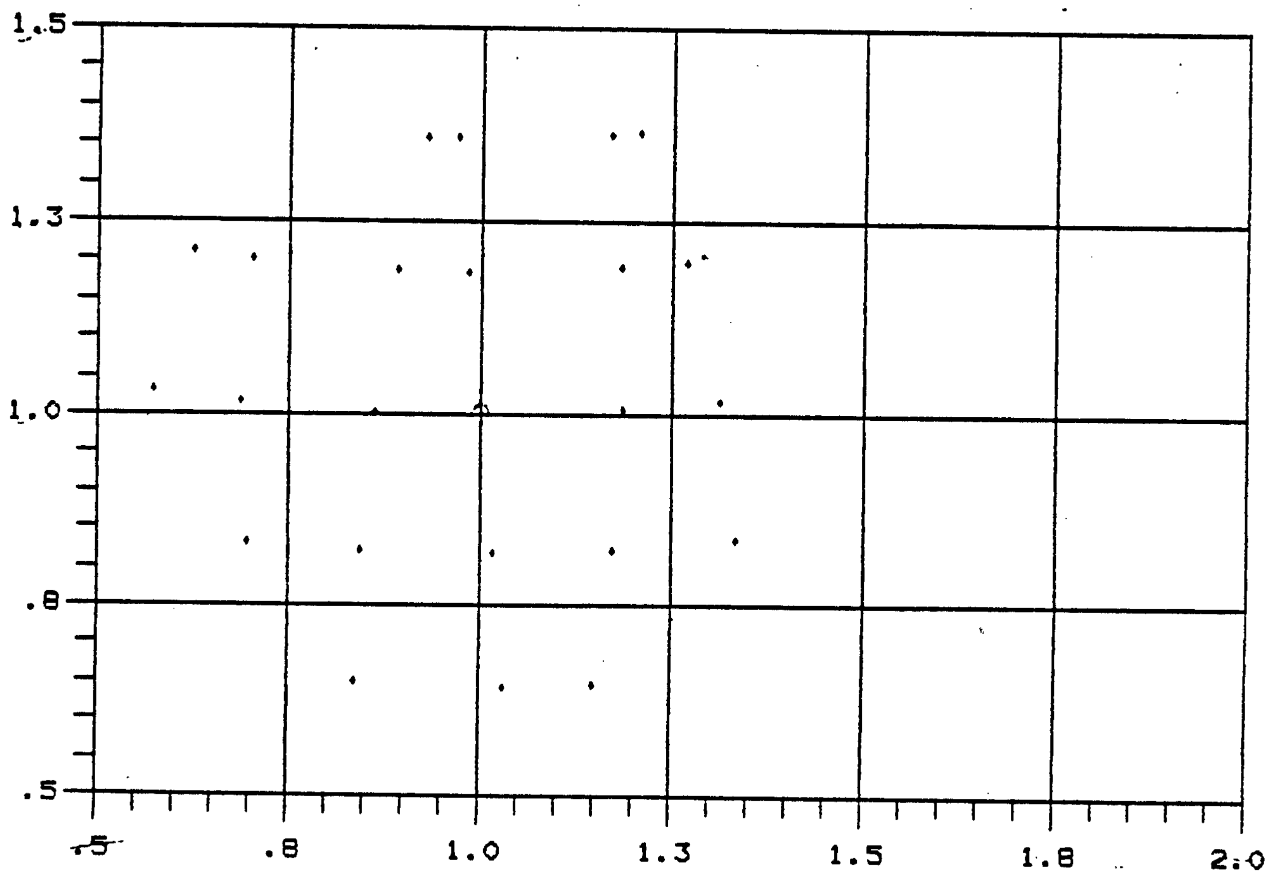
Viewer at 1.0, 1.0

Units = 10,000 KM

Figures III-5, 6, and 7 depict the angular diversity available among the CV/SBI-to-CV/SBI links from a CV/SBI satellite positioned at a point above the equator (the point where the fewest are visible). The same three views (back, side, and top) as the previous three charts are shown and some doubling-up of satellites occurs in the side and top views. The angular diversity is similar to the previous three charts, but the total number of available LOS links is about one-third as many.

FIGURE III-5

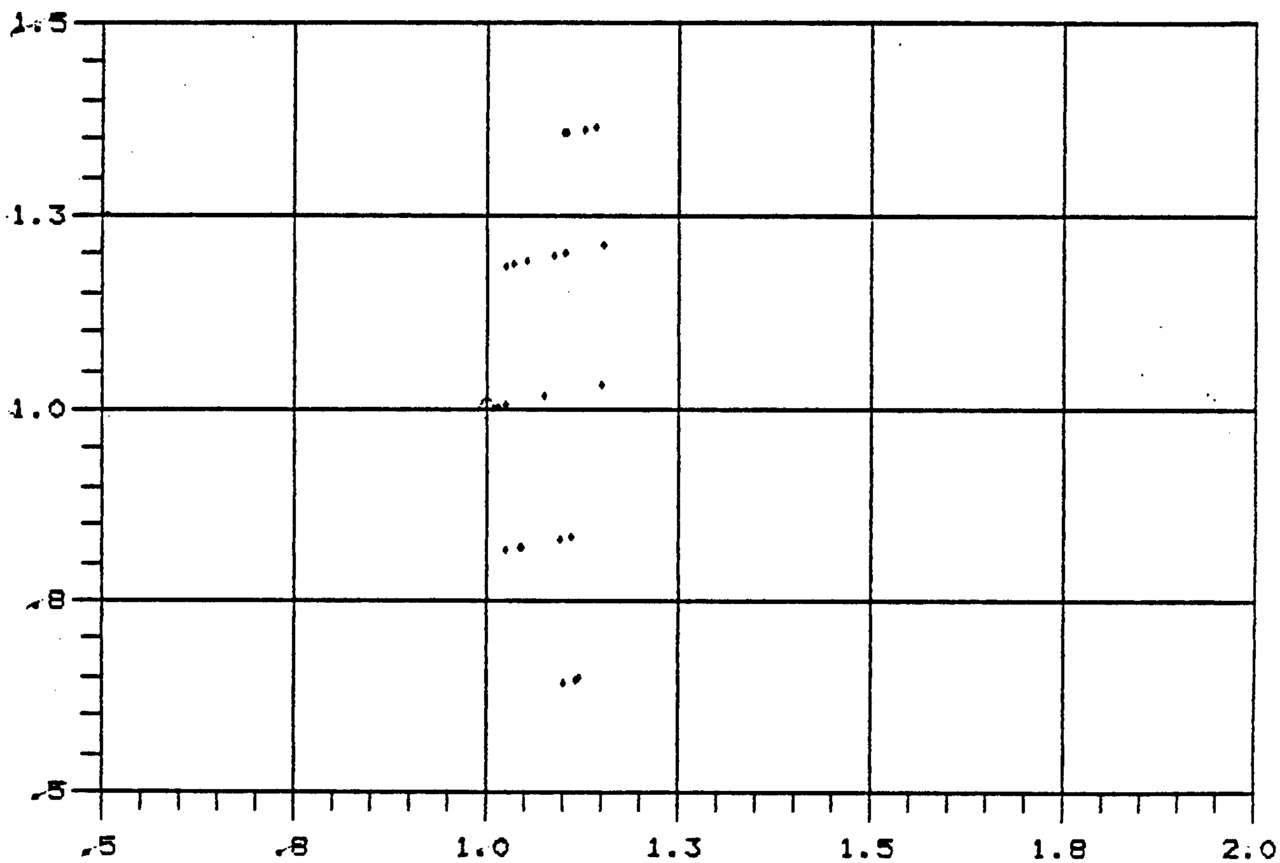
Back View (CV/SBI to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM

FIGURE III-6

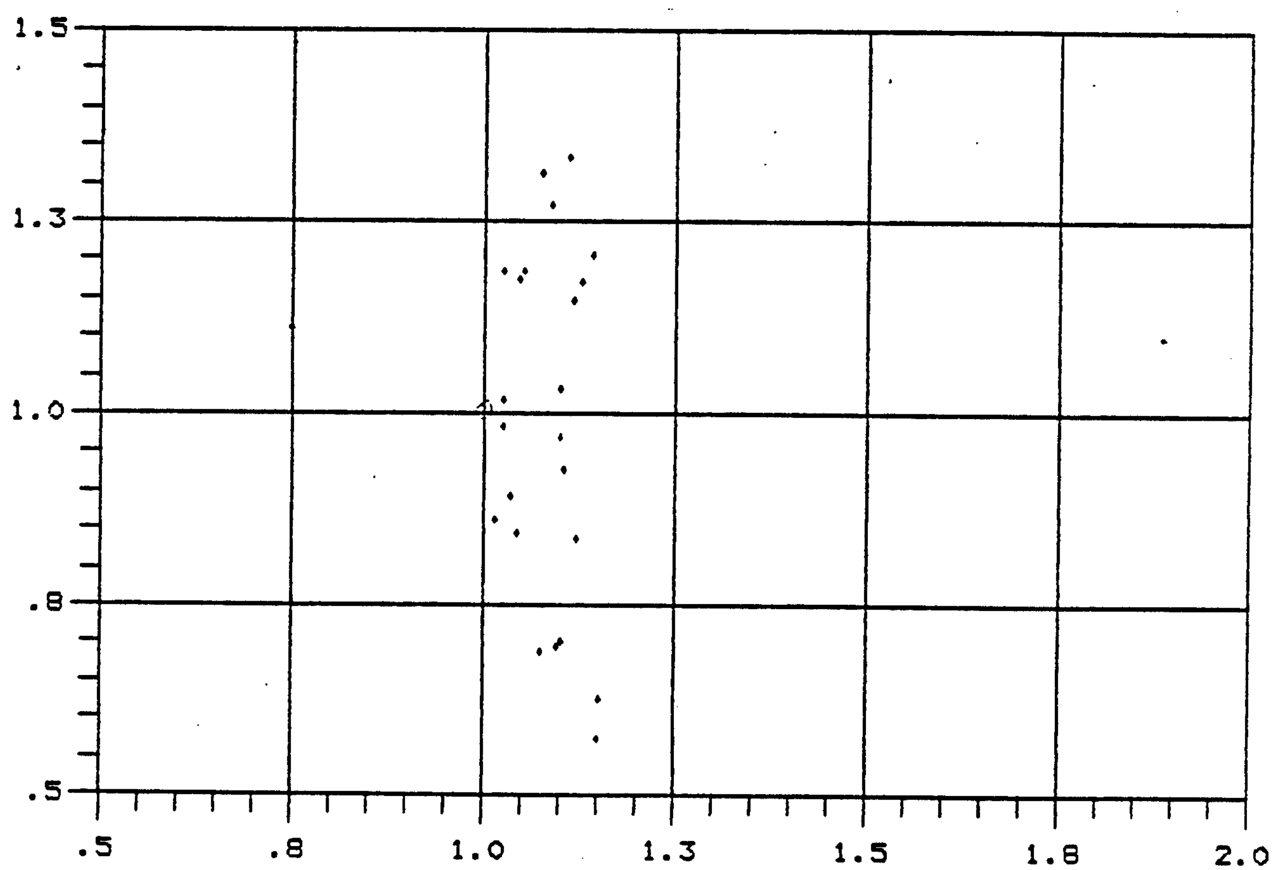
Side View (CV/SBI to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM

FIGURE III-7

Top View (CV/SBI to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM

In summary, more than twenty and as many as sixty LOS CV/SBI-to-CV/SBI links are available from the orbital geometry and back-view links exists around 360°. Side-view and top-view links exist around nearly 180°, and some bunching of satellites at certain radial positions occurs. This configuration allows for an extremely robust angular diversity of links and it also supports a large number of links. To insure a robust architecture, ten of the many available links are arbitrarily chosen as sufficient to provide significant angular and parallel diversity. Analysis later will show this choice is probably higher than required for robustness, link margin, and bit-error rate (BER); nevertheless, generating architectural implications (data rates, size, weight, power, etc.) of ten links will provide a surplus margin that can easily support fewer links.

The question which will remain beyond the scope of this report is just how far relaying should go. For example, in Phase 1 should BSTS-to-CV/SBI-to-CV/SBI relay links be sufficient to negate potential jammers and potential nuclear events or should BSTS through several CV/SBIs to CV/SBI be adopted? Before that question can be answered, analysis must be performed to determine how the relaying should take place: The shortest CV/SBI to CV/SBI links? The longest? Some pseudo-random selection process of ten from all those within LOS? An educated guess from those studying this geometry is that single or double relays pseudo-randomly selected from among those links at a medium

distance (eliminate the nearest since a nuclear event is most likely to affect several in close proximity, and eliminate the furthest as not providing as much jam resistance because of range). Should the SDI/SDS baseline evolve to where partitioning of data is deemed favorable due to battle-management considerations, the partitioning would have to be taken into account and the level of robustness used to alleviate nuclear interference would be degraded somewhat.

CV/SBI-SSTS Links

Figure III-8 and 9 represent the number of SSTS satellites that can be seen from a single CV/SBI satellite as it traverses an orbit. The differences between the charts occur because of differences in the relative phases from orbit to orbit. The main point is that generally a CV/SBI can see four to six (occasionally seven) SSTS satellites, and for the purpose of describing a robust architecture here, the fact that a minimum of four (each at a significantly different angle) are visible is satisfactory.

Two sets of back, side, and top views of the CV/SBI-to-SSTS geometries follow in Figure III-10 through 15, and these charts show the representative angular diversity.

FIGURE III-8

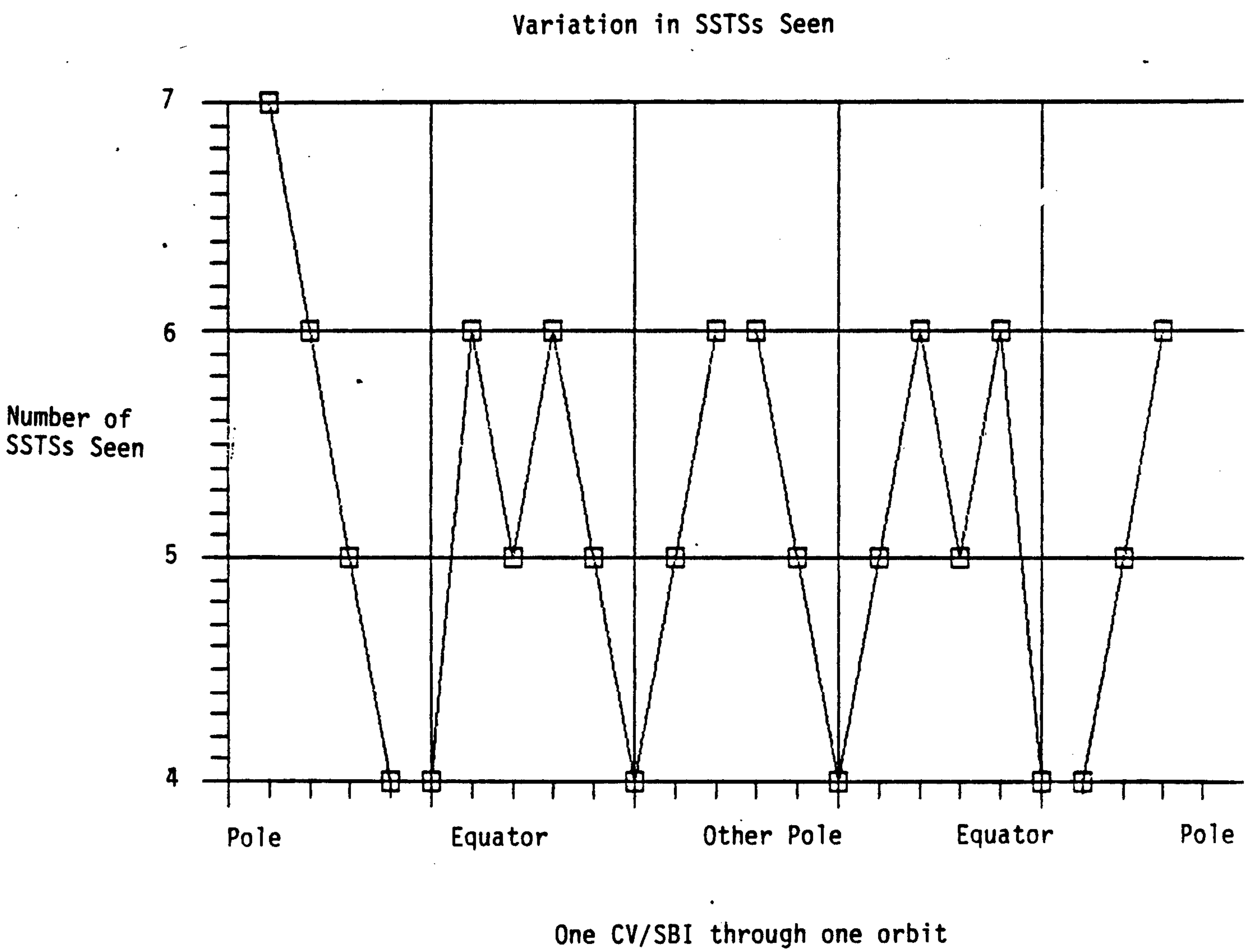

Variation in SSTSs Seen
7
6
5
4
Number of
SSTSs Seen
Pole
Equator
Other Pole
Equator
Pole
One CV/SBI through one orbit

FIGURE III-9

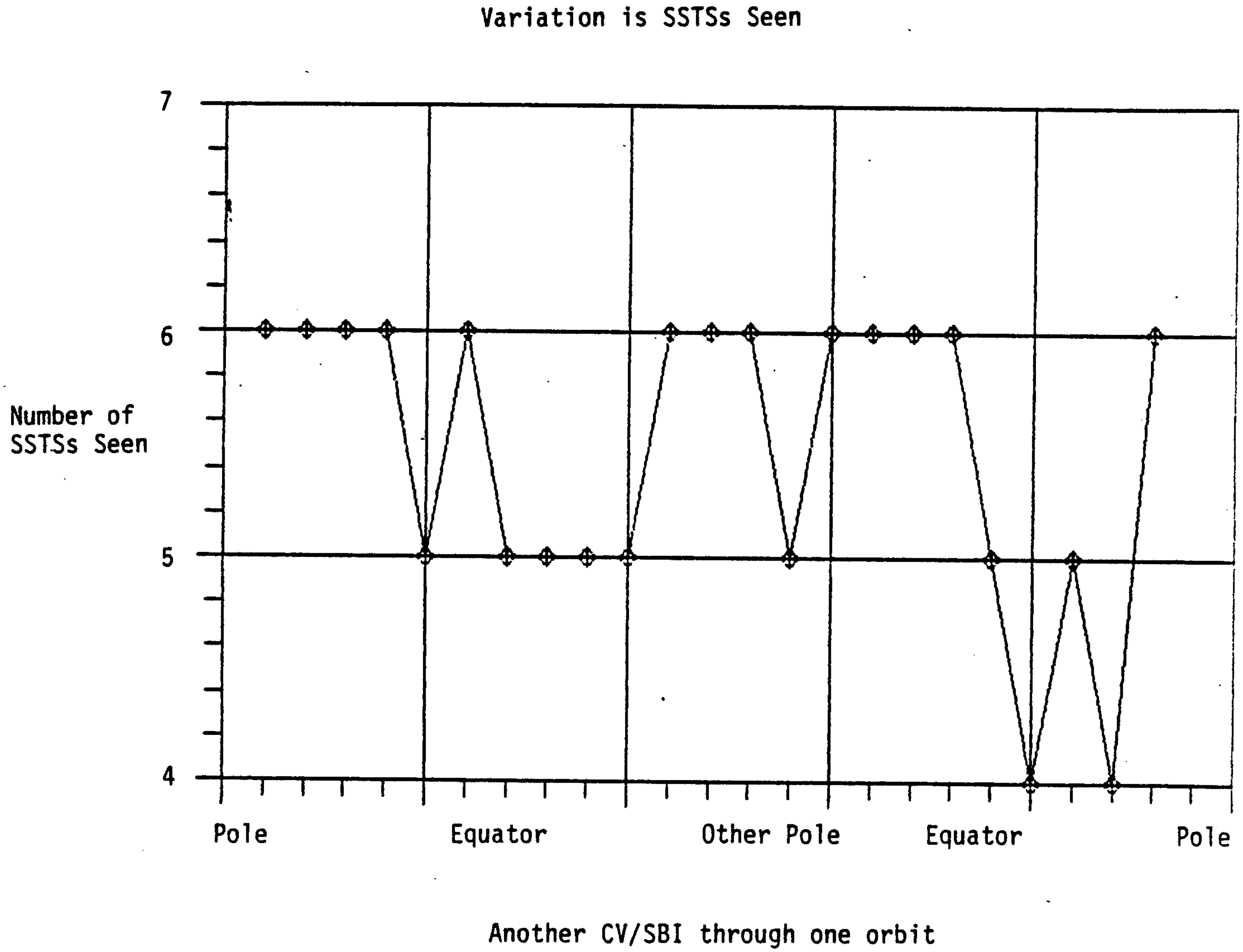
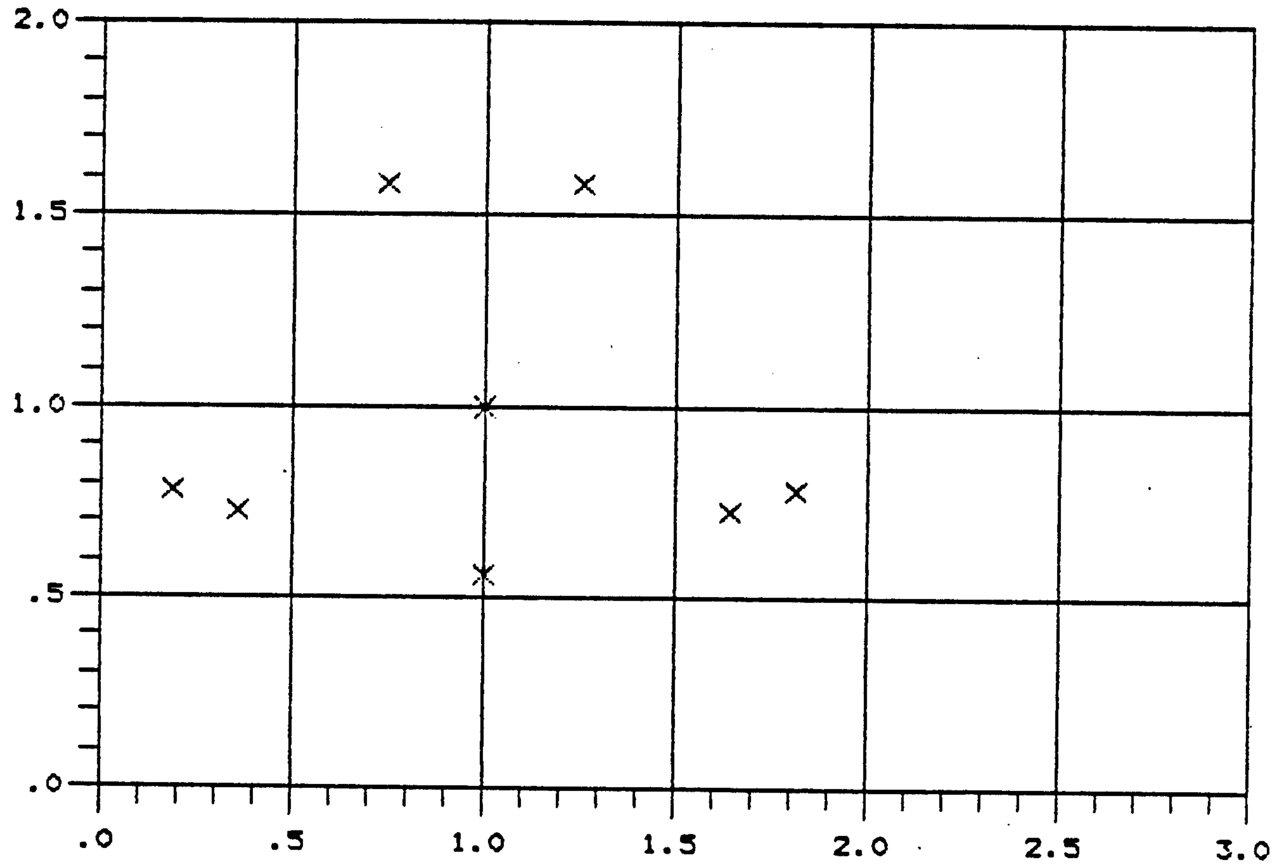

Variation is SSTSs Seen
7
6
5
4
Number of SSTSs Seen
Pole
Equator
Other Pole
Equator
Pole
Another CV/SBI through one orbit

FIGURE III-10

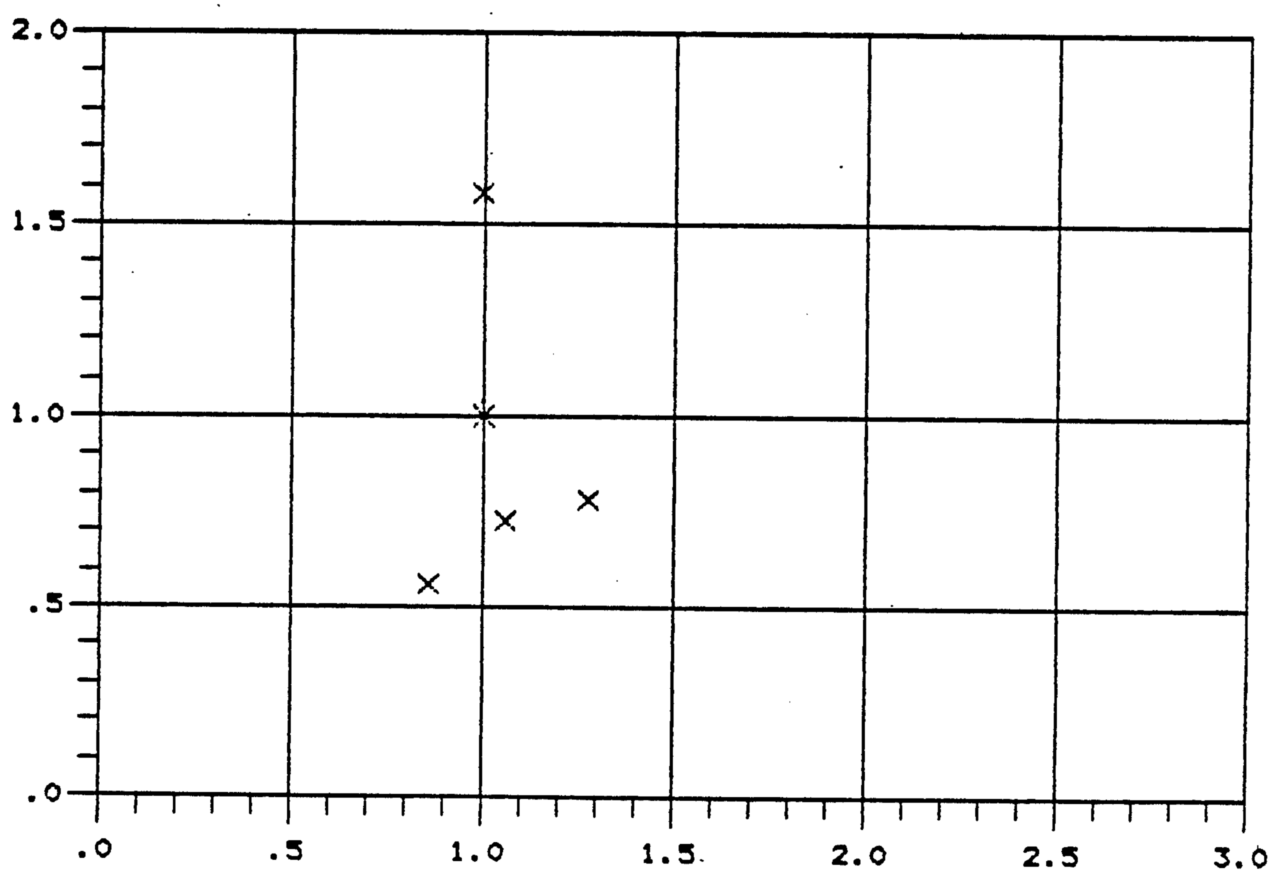
Back View (CV/SBI to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-11

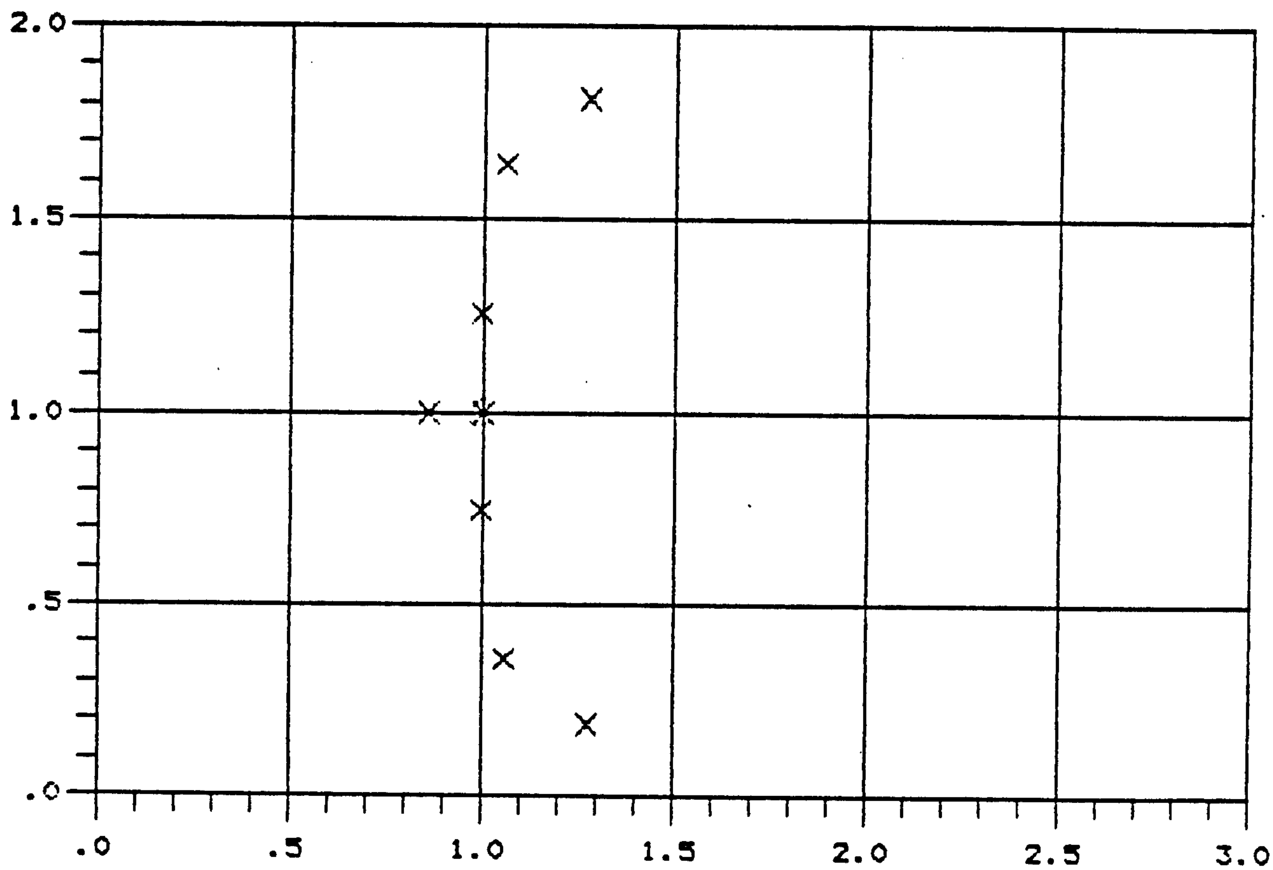
Side View (CV/SBI to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-12

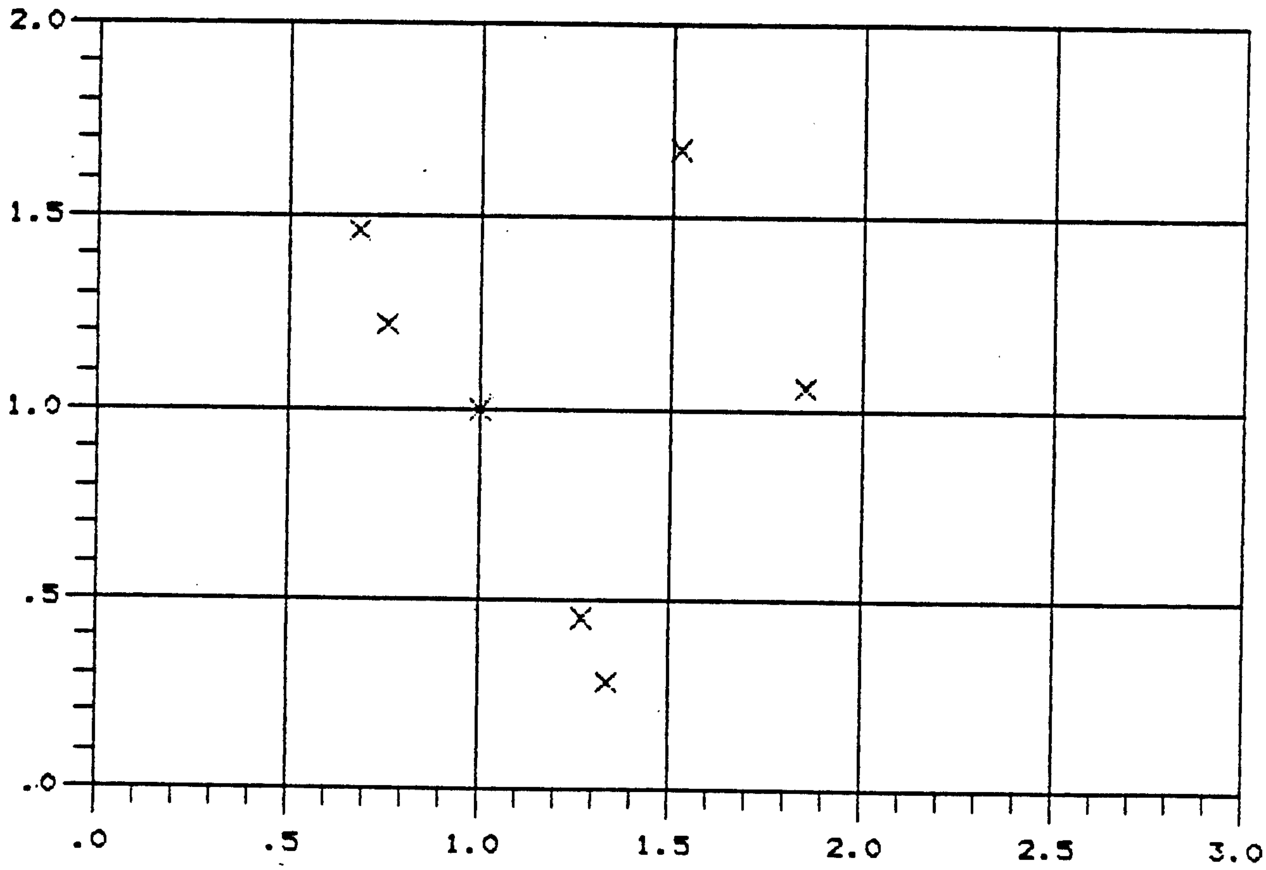
Top View (CV/SBI to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-13

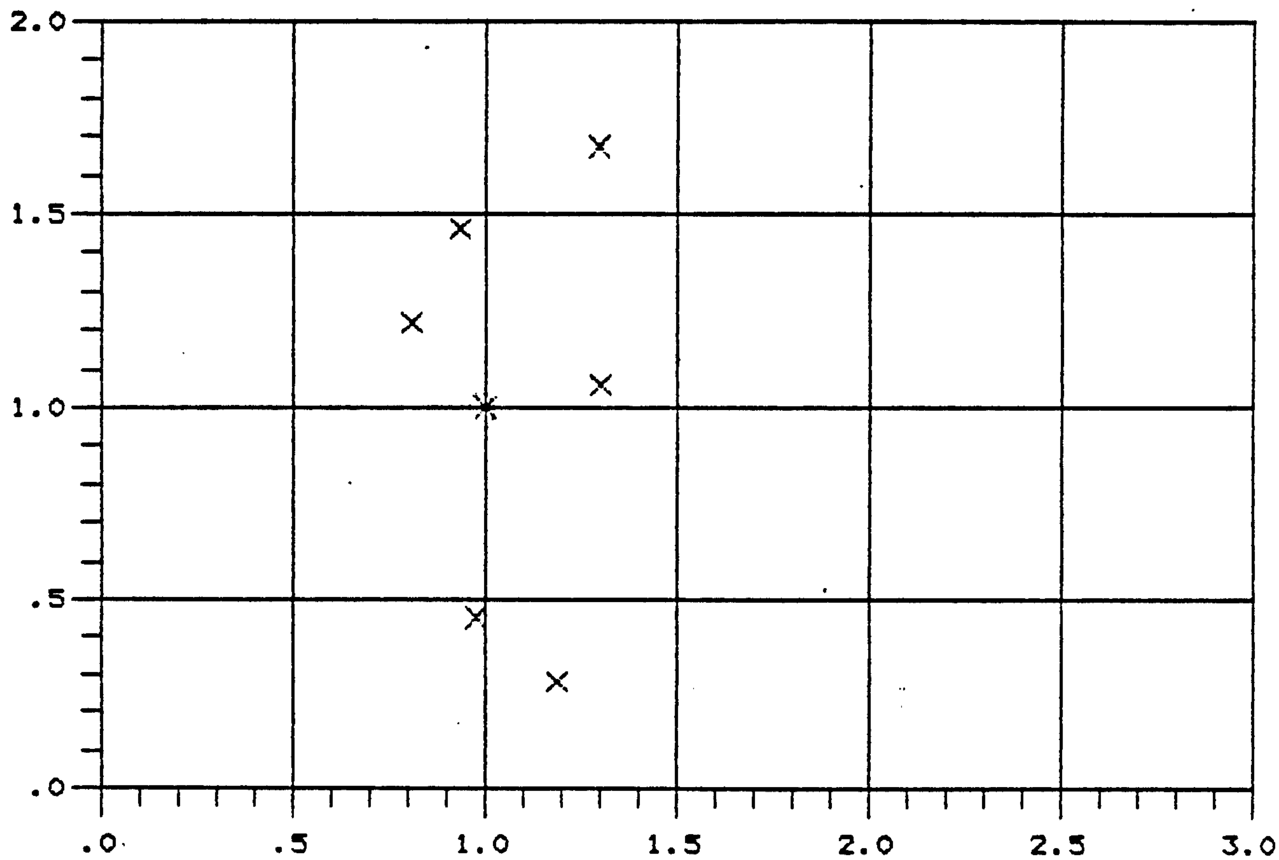
Back View (CV/SBI to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 2)

FIGURE III-14

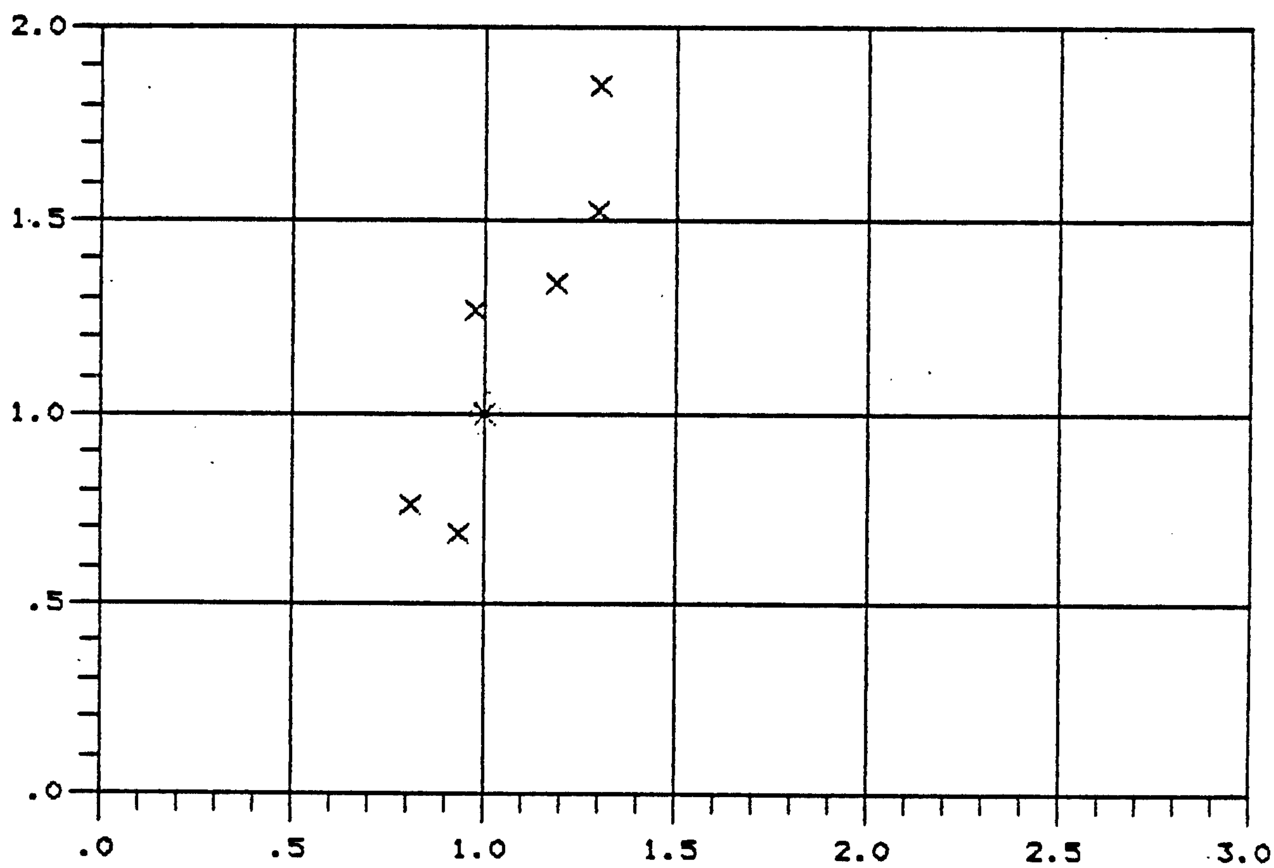
Side View (CV/SBI to SSTSs)



Viewer at 1.0, 2.0
Units = 10,000 KM
(Set 2)

FIGURE III-15

Top View (CV/SBI to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 2)

In summary, at least four SSTS satellites are always visible, and the back view supports 360° of angular diversity. The side and top views tend to be in a broad line to both "sides" of the CV/SBI satellite. In actuality, this angular configuration lends itself to a robust amount of angular diversity (back view) while not over complicating the demands (side, top views) put upon an antenna system. A relatively small, yet marginally very significant (as is shown later), number of links can be supported. For purposes here, two of the four links are selected for robustness. This link primarily provides for health and status information--not of the highest priority. And, as before, analyses to determine that exactly two of the four available links are best (if they are) and which two to use are beyond the scope of this report.

CV/SBI-BSTS Links

Figures III-16 and 17 depict two representative variations of the BSTS satellites from the CV/SBIs. Depending upon the relative phase of the CV/SBI satellite, either three or four BSTSs will generally be seen, except when near the poles where six are visible.

Again, "Health and Status" is the primary linkage and the relative priority of the information is low. It is not clear that multiplying the connectivity of any of these links is necessary.

FIGURE III-16

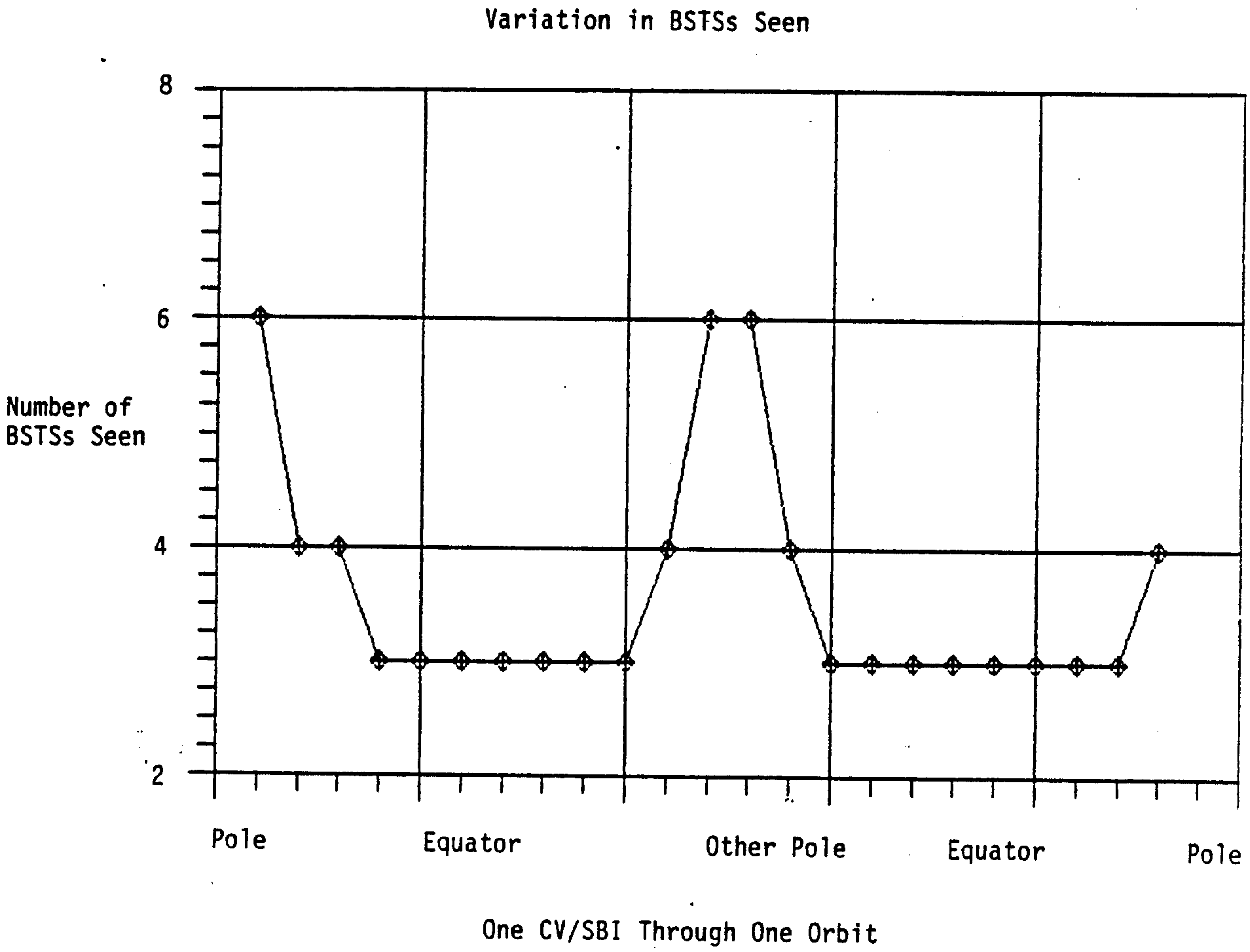
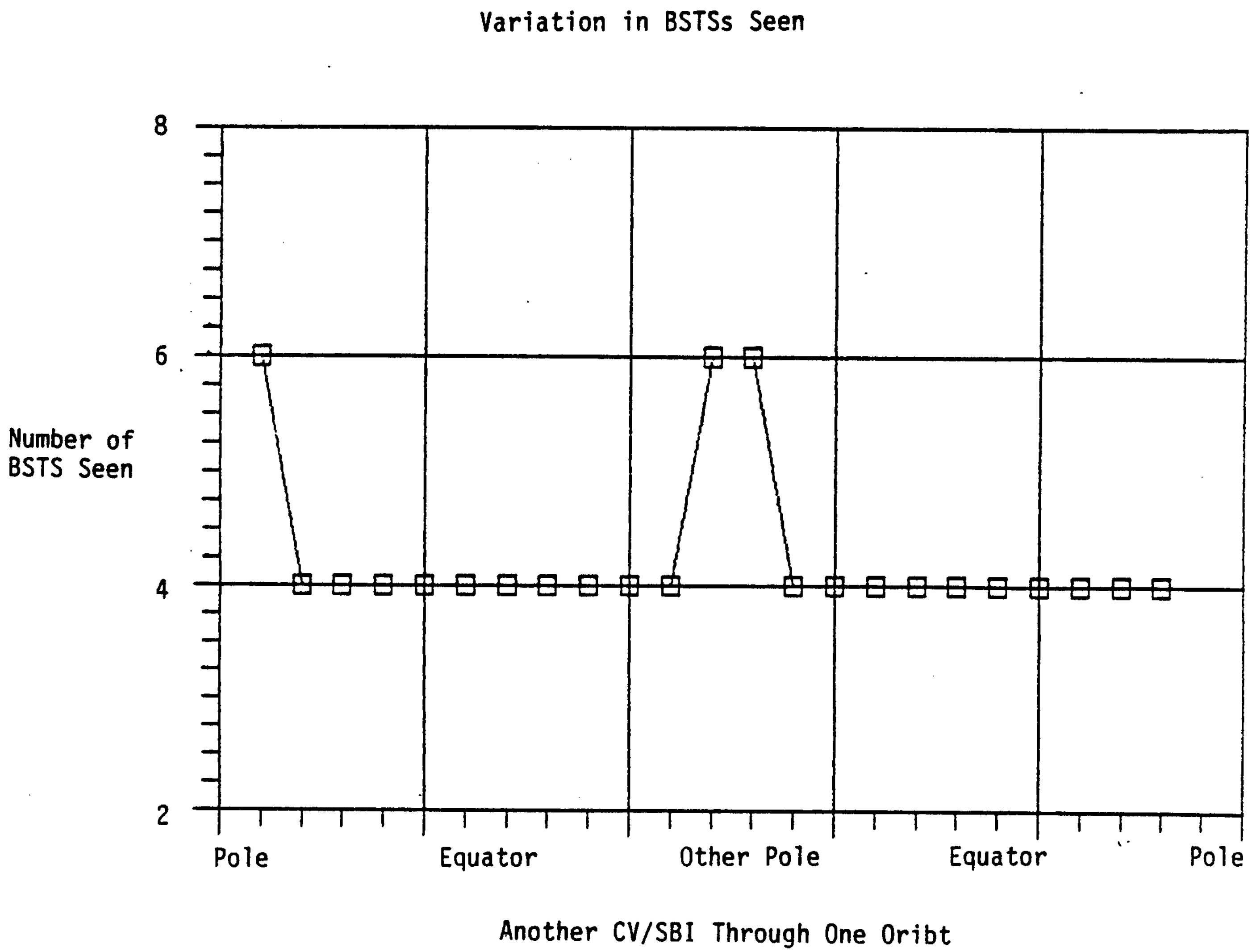


FIGURE III-17



SSTS-CV/SBI Links

From 60 to 110 CV/SBIs are visible from an SSTS at any point in time. Figures III-18 and 19 show two representative orbits with six samples per orbit. (The two views represent two SSTSs that are phased differently, but representively within two separate SSTS orbital planes.)

Figures III-20, 21, and 22 show the back, side, and top views which demonstrate the angular diversity of the CV/SBIs within LOS from an SSTS positioned high (toward the North Pole) in it's orbit. Whereas Figures III-23, 24, and 25 show the same views of angular diversity from an SSTS that is positioned above a point close to the equator.

In summary, the back view shows some small amount of bunching around a full 360^{o} of diversity, with top and side views showing nominal bunching through about 180^{o}. Up to 60 links can be maintained LOS from the geometry. In Phase 2 this is a critical data link and parallel lines of connectivity are expected to be of value. The high data rate works against supporting too many links. For purposes here, as a strawman, 34 distinct links from each SSTS is selected. Therefore, some redundancy in each link is maintained.

FIGURE III-18

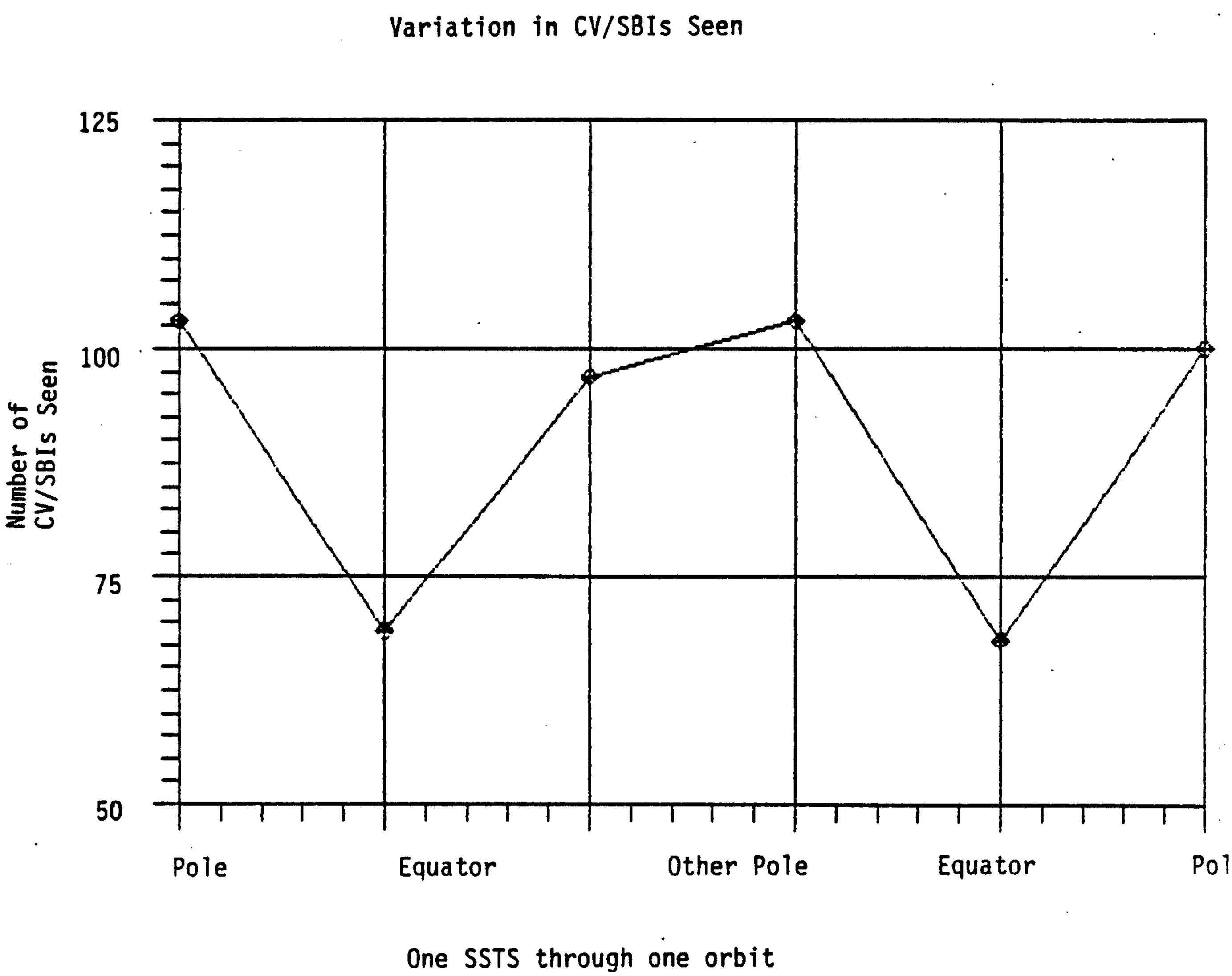


FIGURE III-19

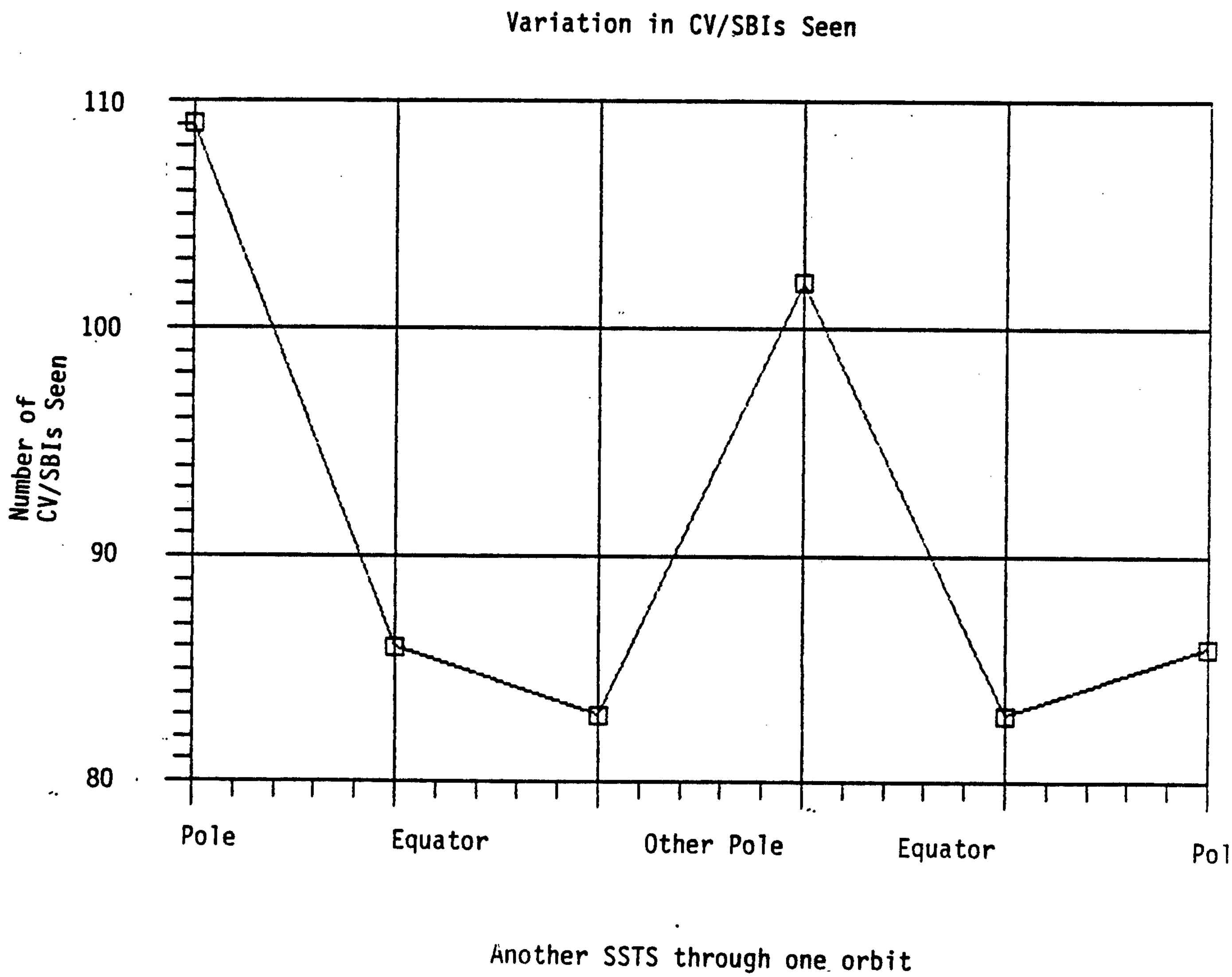
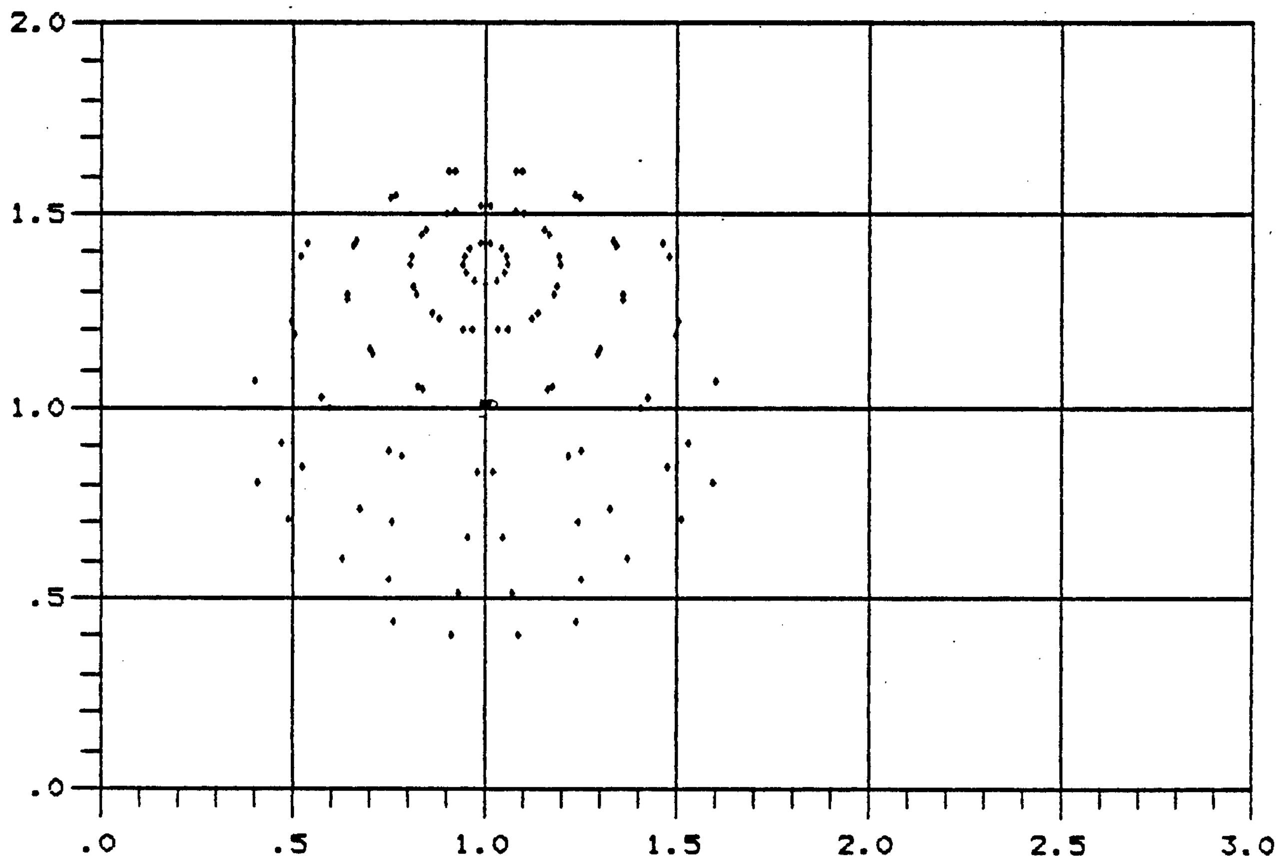


FIGURE III-20

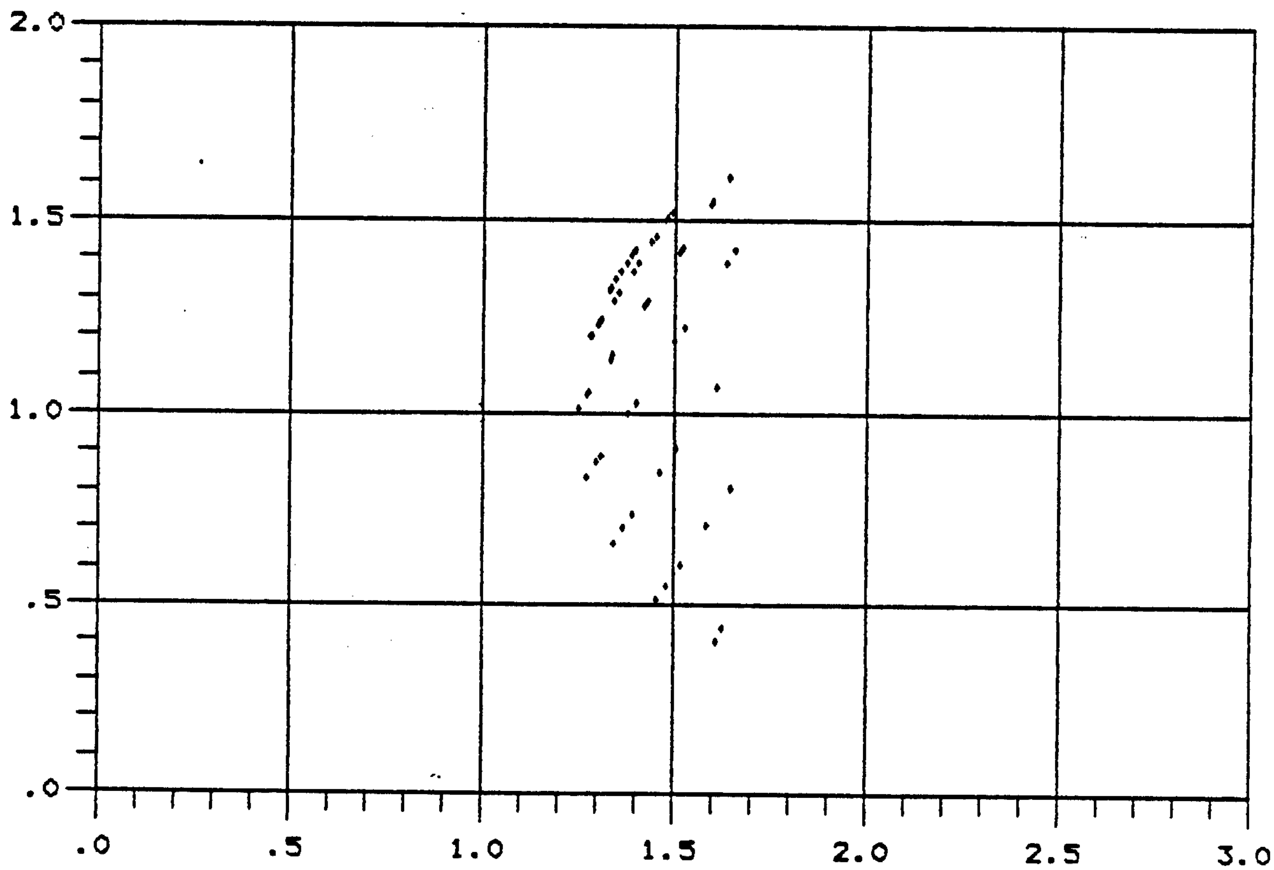
Back View (SSTS to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-21

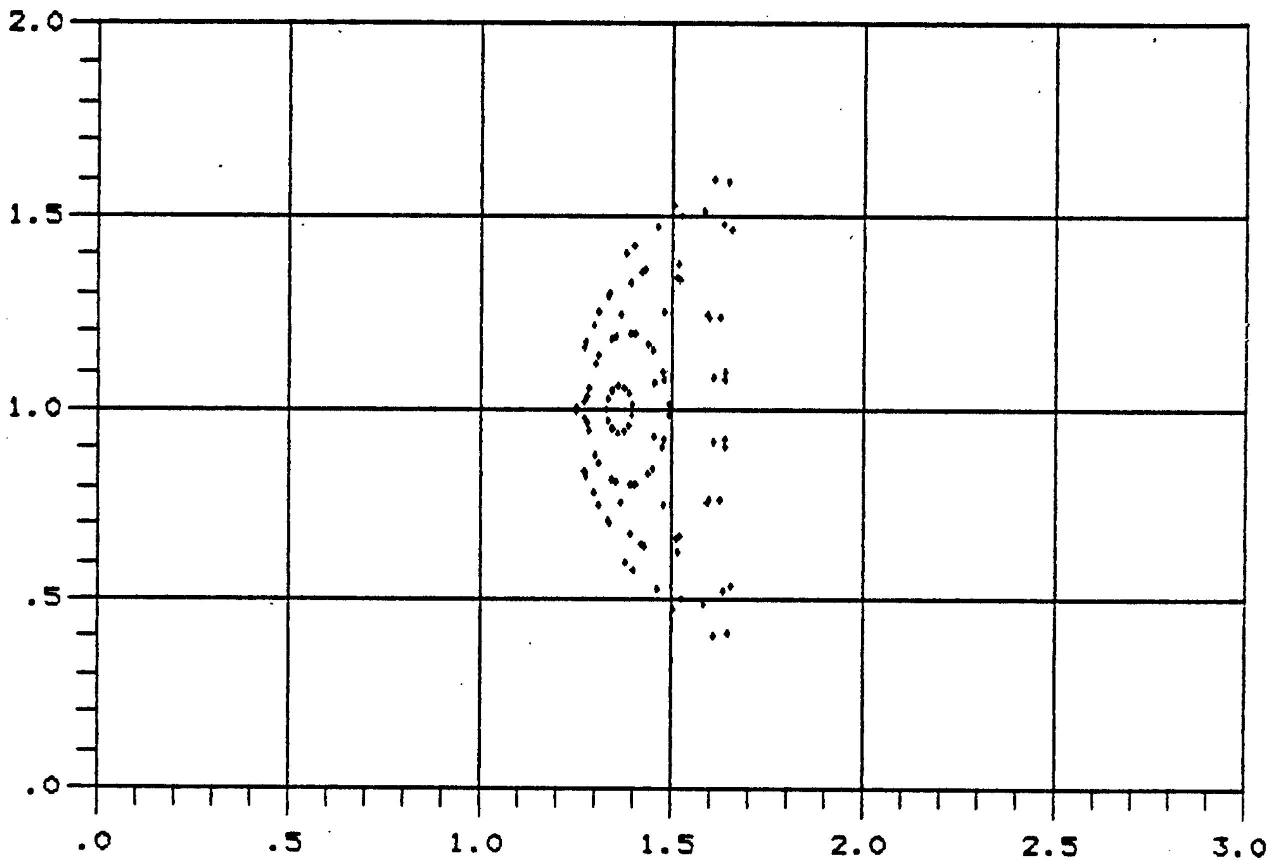
Side View (SSTS to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-22

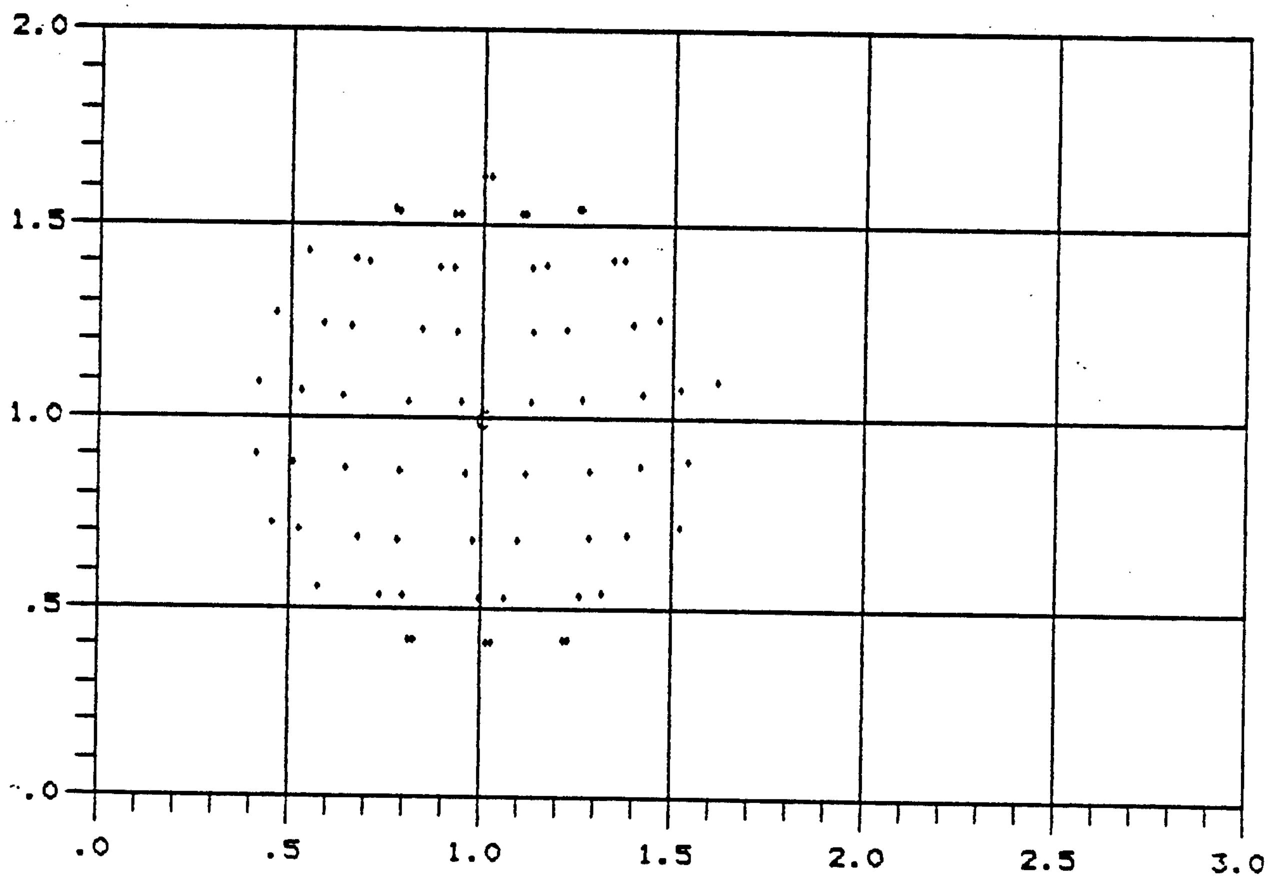
Top View (SSTS to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-23

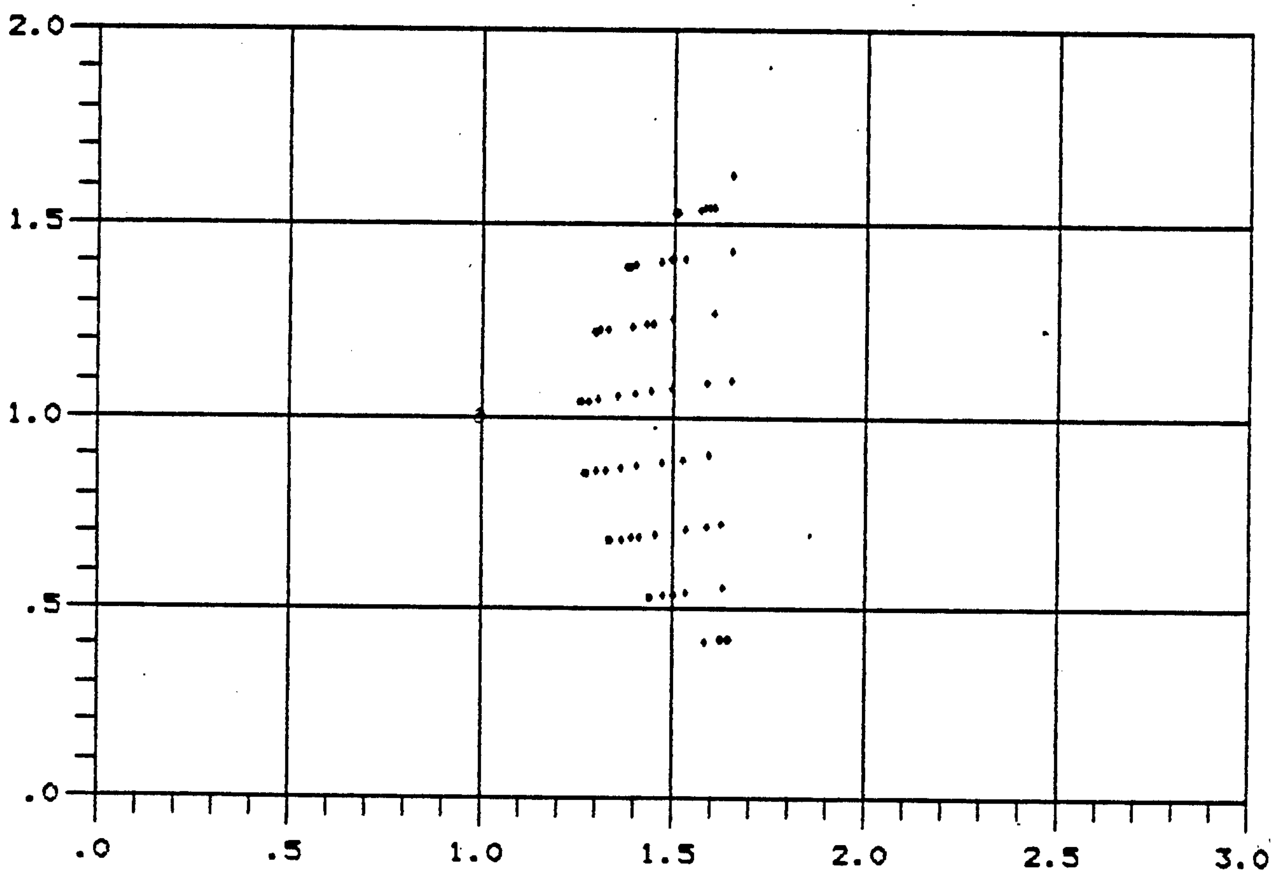
Back View (SSTS to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 2)

FIGURE III-24

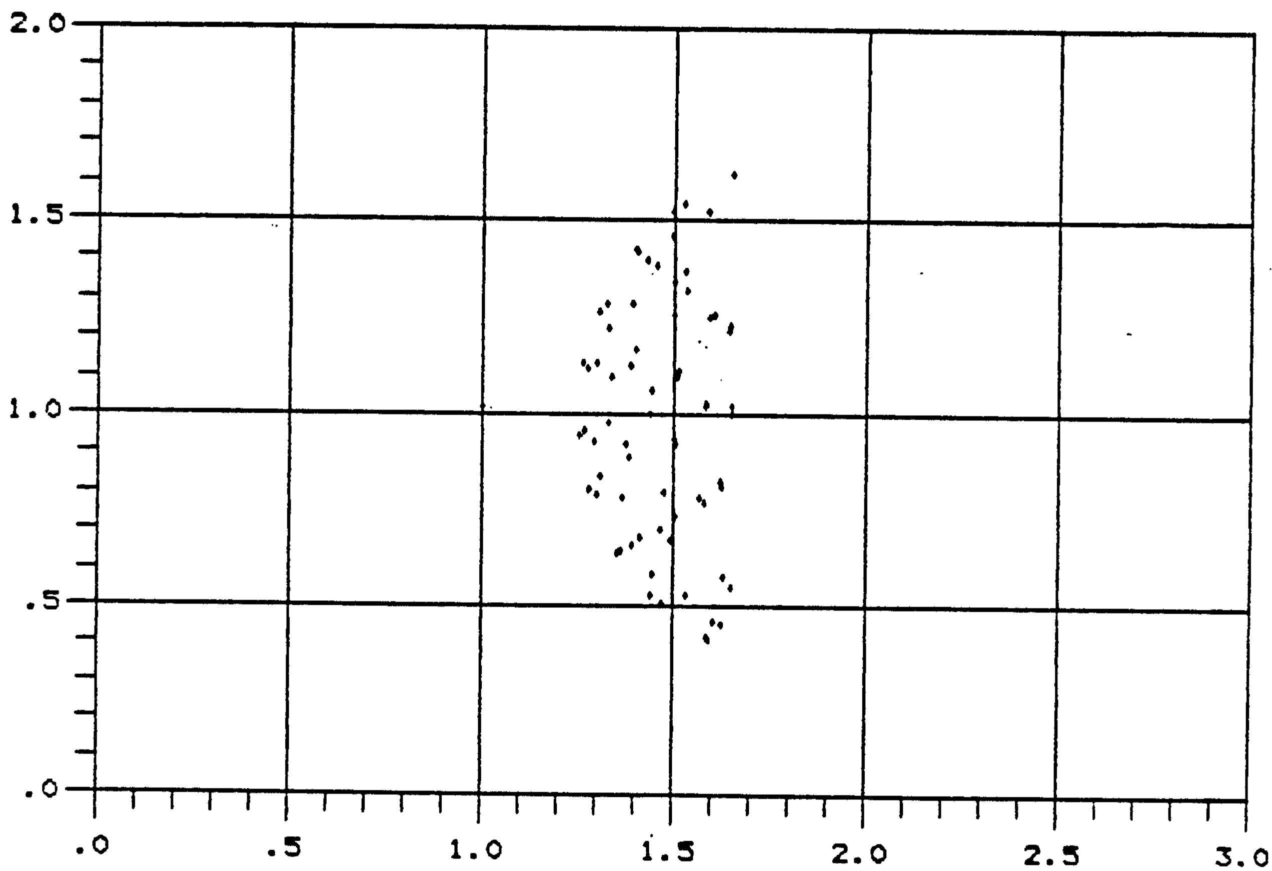
Side View (SSTS to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 2)

FIGURE III-25

Top View (SSTS to CV/SBIs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 2)

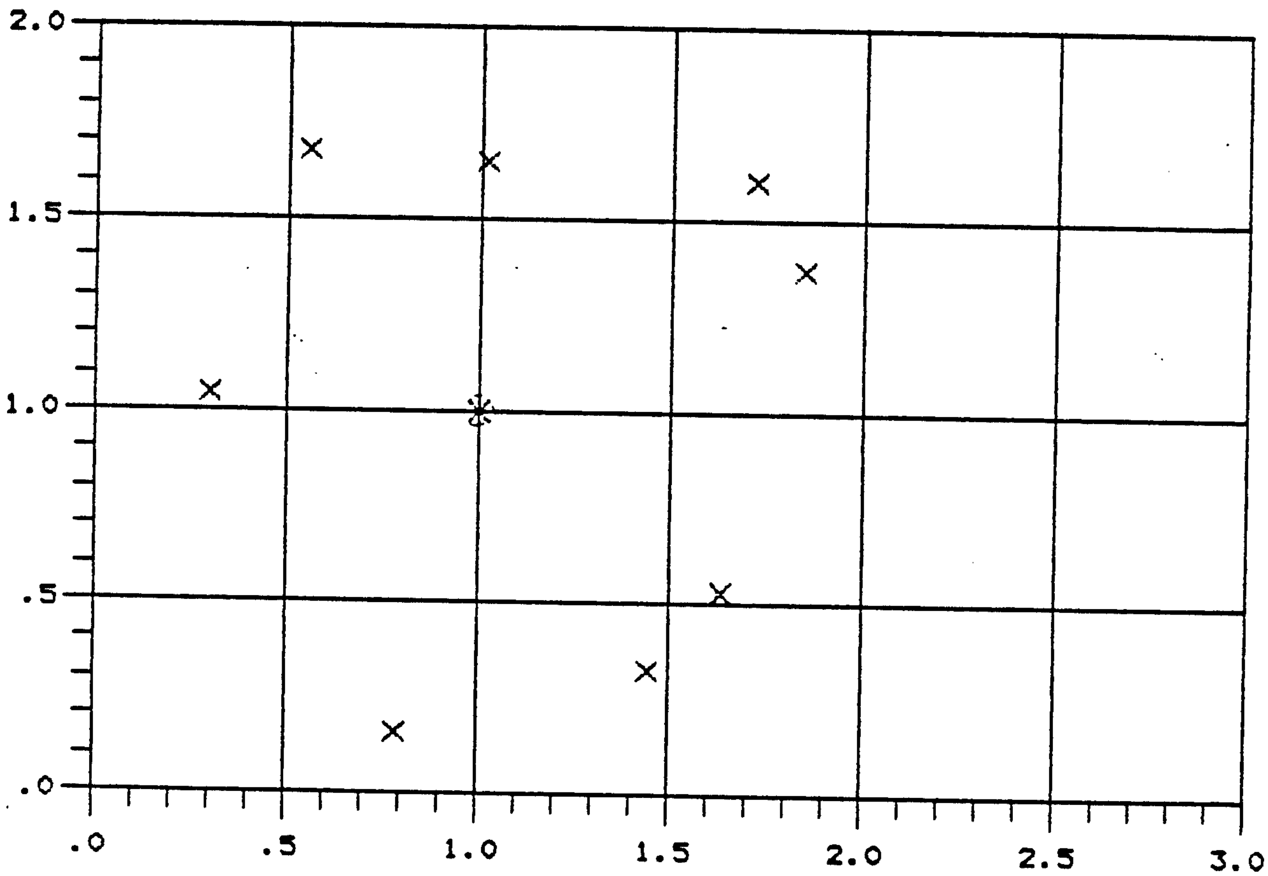
SSTS-SSTS Links

No chart showing the number of SSTSs visible from an SSTS is included since, for all orientations, the number is exactly eight. Two sets of back, side, and top views are shown in Figures III-26 through 31 to depict the angular diversity. The two views represent different phases of the satellite's orbits--together, the views are representative.

These links support a very high data rate and eight parallel links are probably too many. The strawman here is four angularly diverse links. Again, the back view shows 360° of angular diversity whereas the top and side views show roughly 180°. It is not clear whether the closest, furthest, or middle links should be chosen or whether they should be pseudo-randomly selected. Inter-orbit, rather than intra-orbit, links provide more angular diversity and more tracking complexity. Where a laser link may be chosen over an EHF link, assuming EHF phased arrays are available and laser antenna agility is much more difficult, laser links may need to stay with the less diverse intra-orbit netting. EHF, on the other hand, may just as easily take advantage of the more diverse inter-orbit netting.

FIGURE III-26

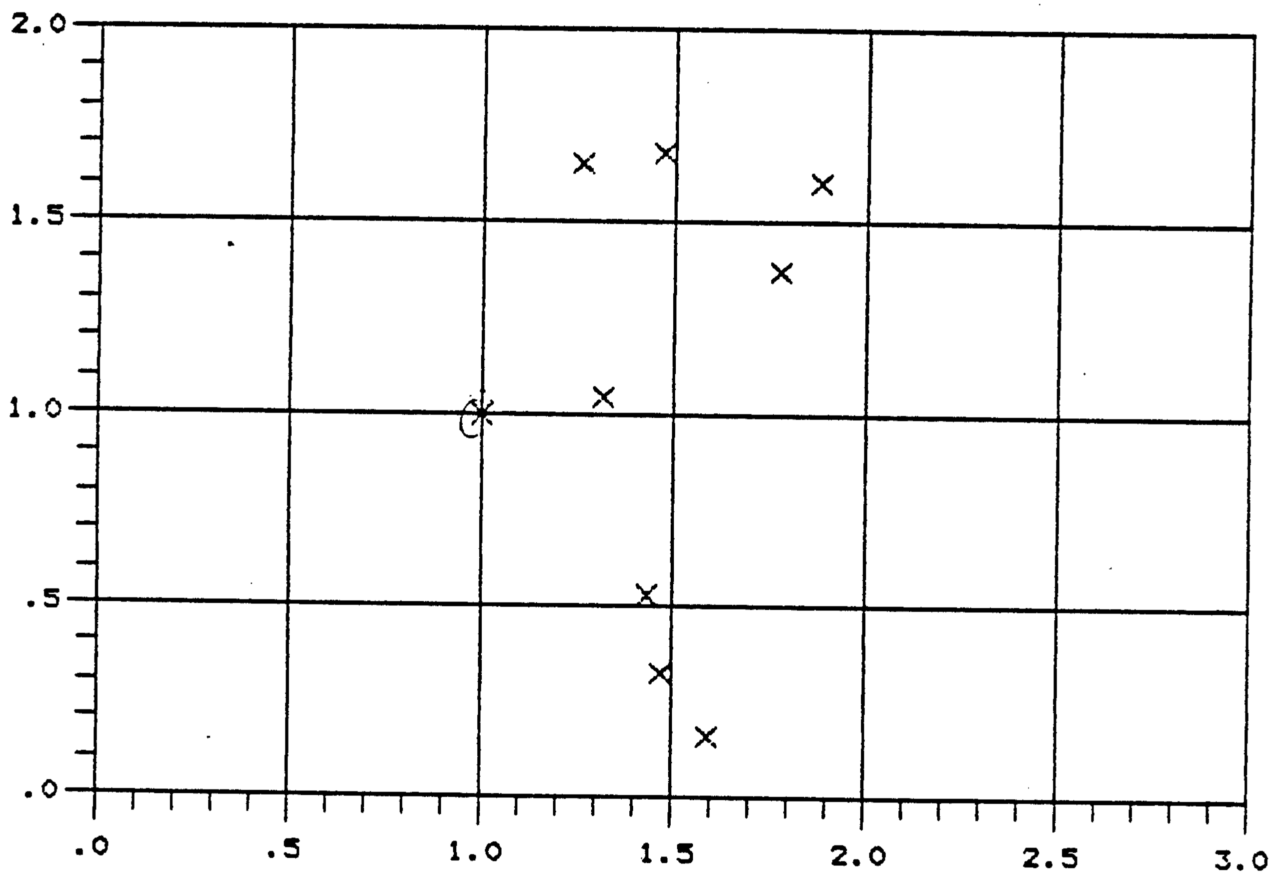
Back View (SSTS to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-27

Side View (SSTS to SSTSs)

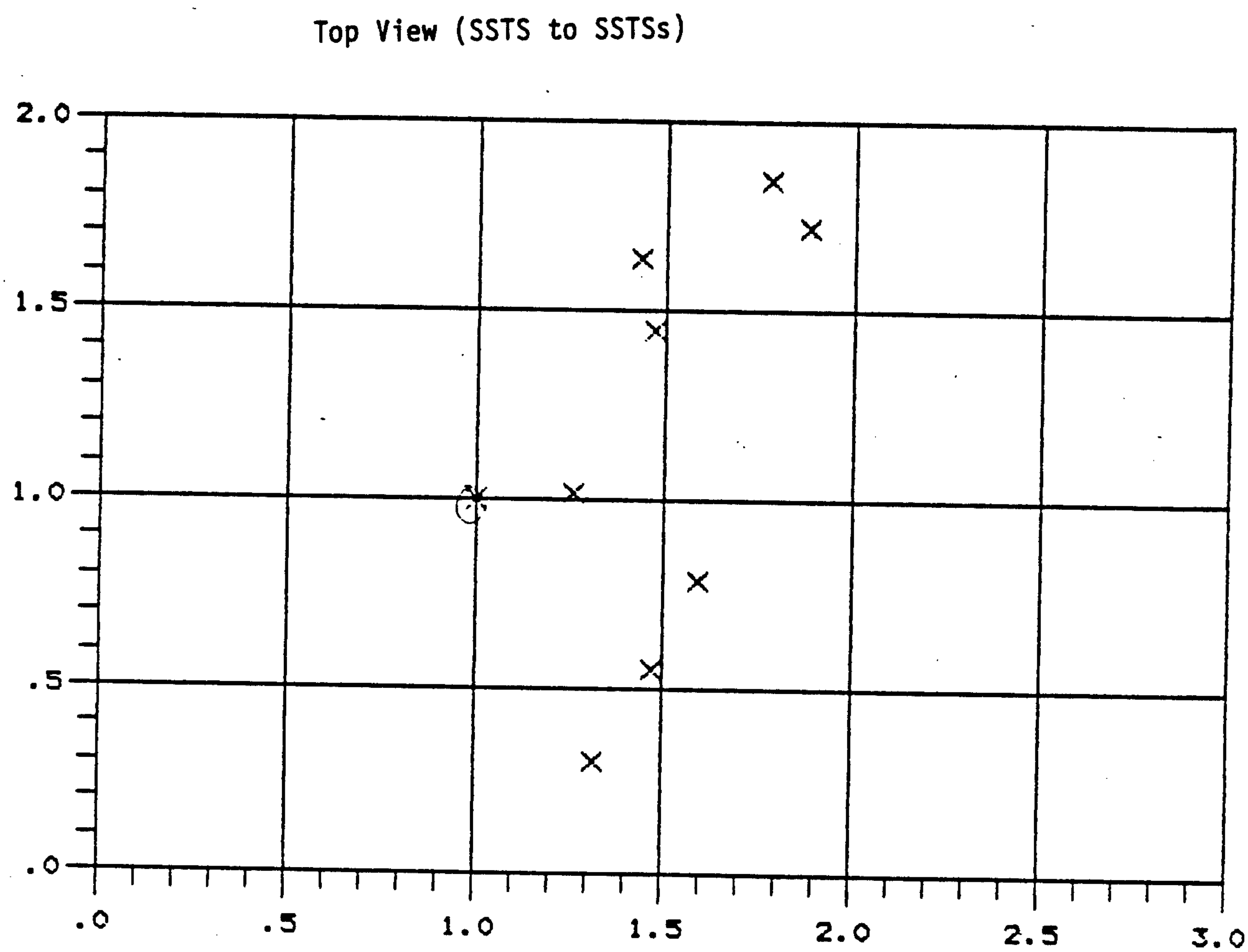


Viewer at 1.0, 1.0

Units = 10,000 KM

(Set 1)

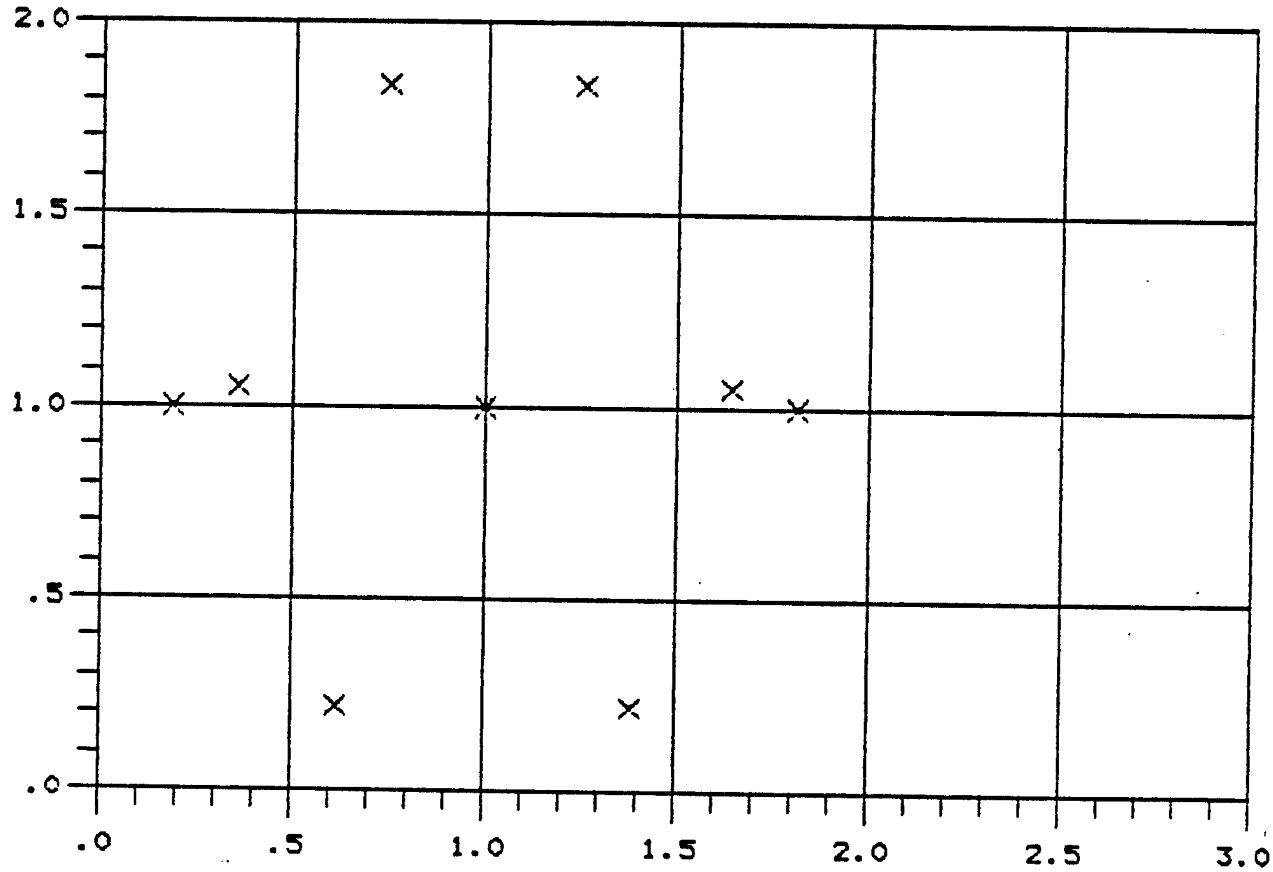
FIGURE III-28



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 1)

FIGURE III-29

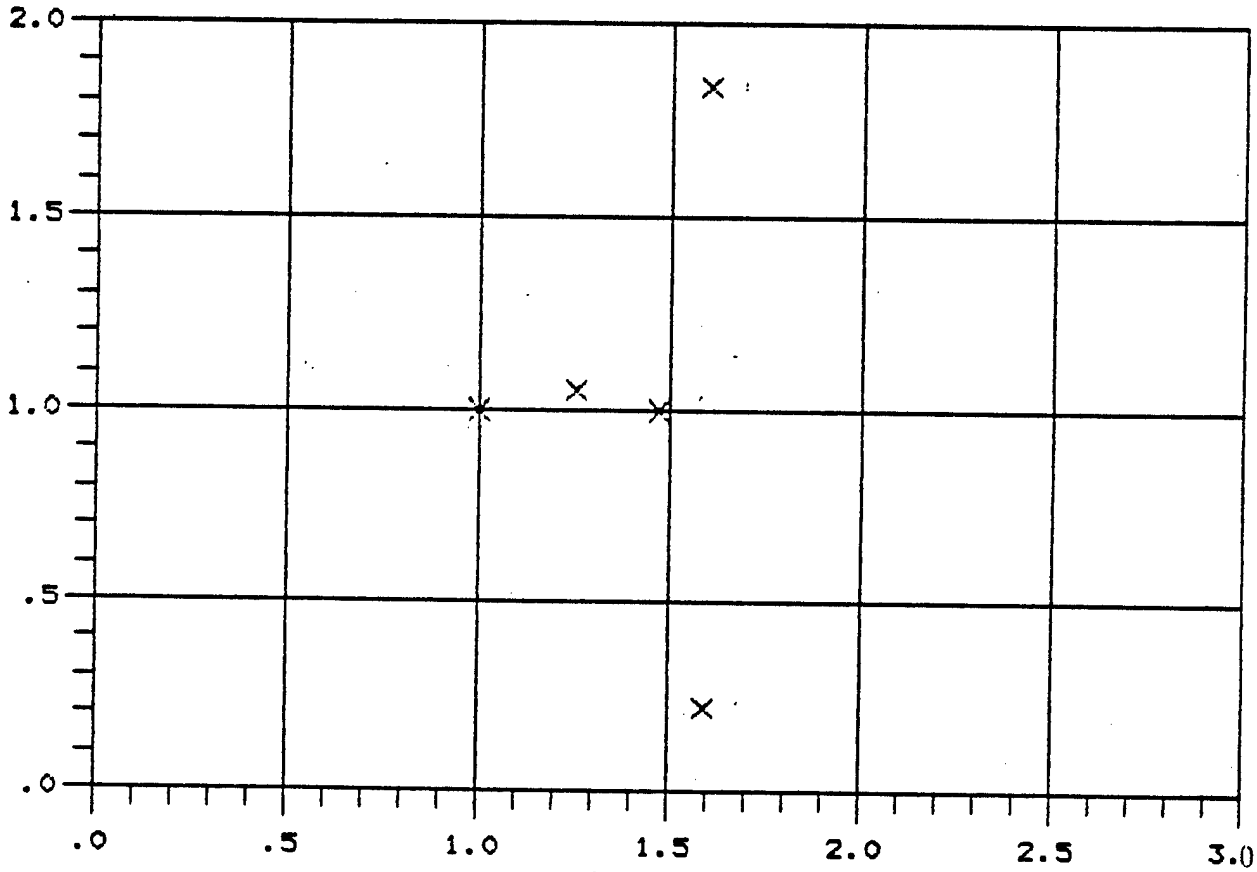
Back View (SSTS to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 DM
(Set 2)

FIGURE III-30

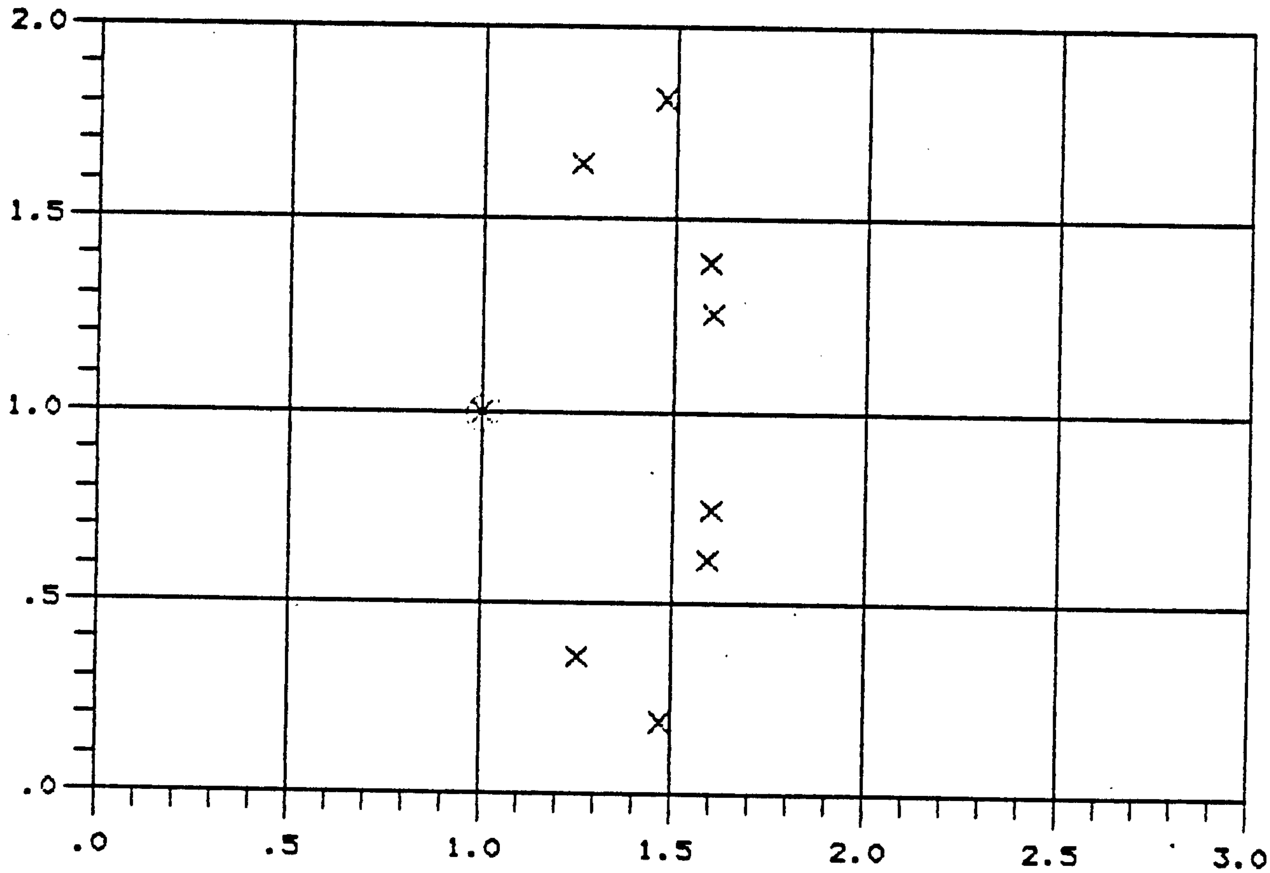
Side View (SSTS to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 DM
(Set 2)

FIGURE III-31

Top View (SSTS to SSTSs)



Viewer at 1.0, 1.0
Units = 10,000 KM
(Set 2)

SSTS-BSTS Links

The SSTS-BSTS angular diversity is obvious. Two or three links can easily be maintained while an additional one is being acquired. This link is not of the highest priority, and while the angular differences are reasonably wide, they track rather routinely, not adding significantly to any sort of covertness. With the small number of BSTS satellites expecting narrow-beam signals from known angles jamming is still a difficult, and probably prohibitively expensive task. More so than most of the other links lasers may tradeoff favorably for this link, but as discussed in Section X, a hybrid EHF/laser communication system for the SDS is very undesirable.

BSTS-CV/SBI Links

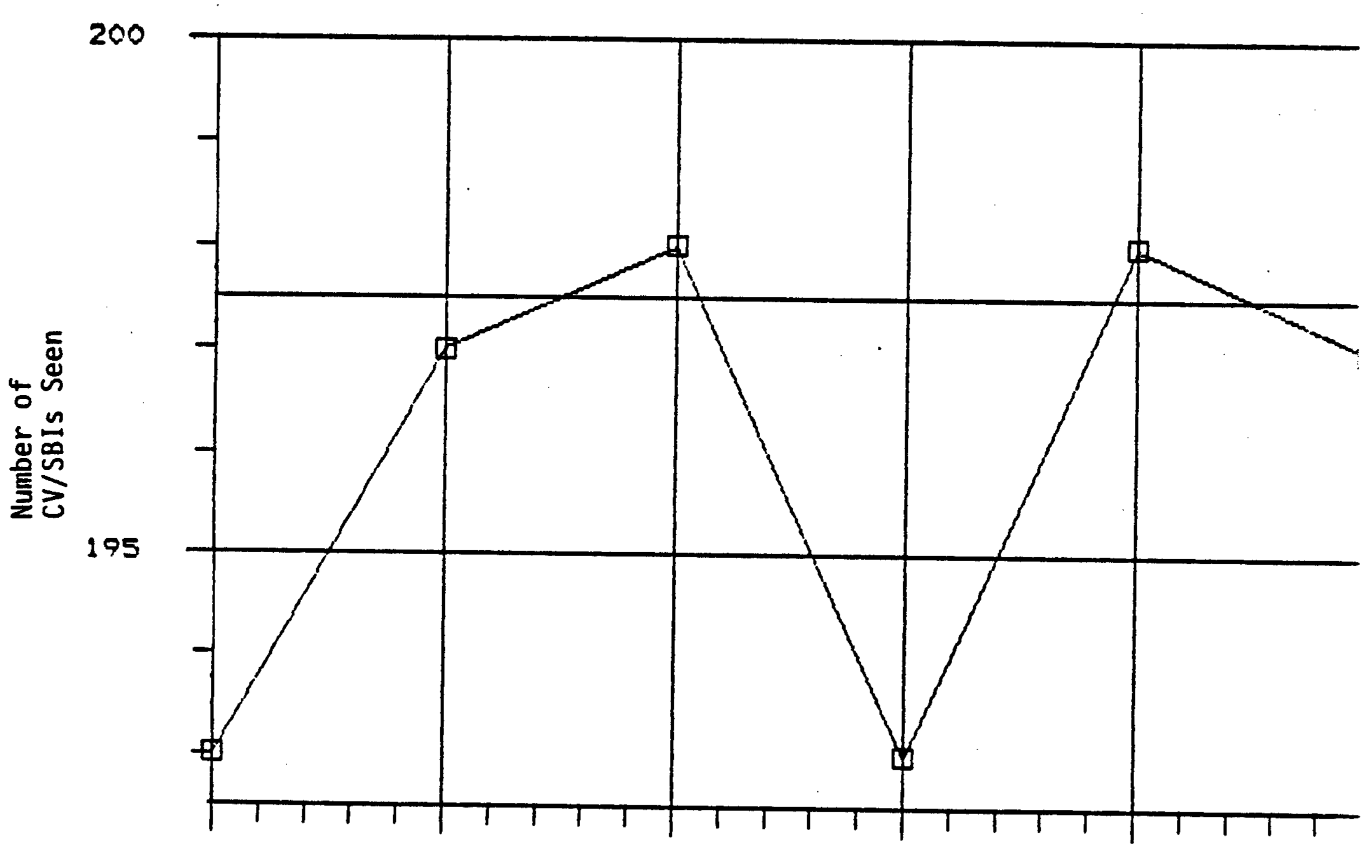
Depending upon orientation, each BSTS satellite can see 190-200 CV/SBI satellites. One representative orbit with six data points is shown in Figure III-32. All the satellites are within a field of view of approximately 19°. A "wide" beam broadcast to all satellites is possible, but well over 30 dB added gain is available by pointing to the individual satellites. Some of the advantage can be gained by narrowing the beam partially and broadcasting to clusters of satellites. Tradeoffs of all potential configurations are beyond the resources of this study.

In a very robust architecture, each BSTS can generate ten beams of TDMA information (fifteen satellites per beam). TDMA must be synchronized to the TOA at each CV/SBI. CDMA orthogonal codes superimposed upon TDMA can be employed to improve separation, if necessary.

For purposes here, this latter approach which supports multiple, high-gain (narrow beam) links is adopted to most effectively guarantee connectivity of this most important link (especially in Phase 1) where both jamming and nuclear interference may pose problems.

FIGURE III-32

Variation in CV/SBIs Seen

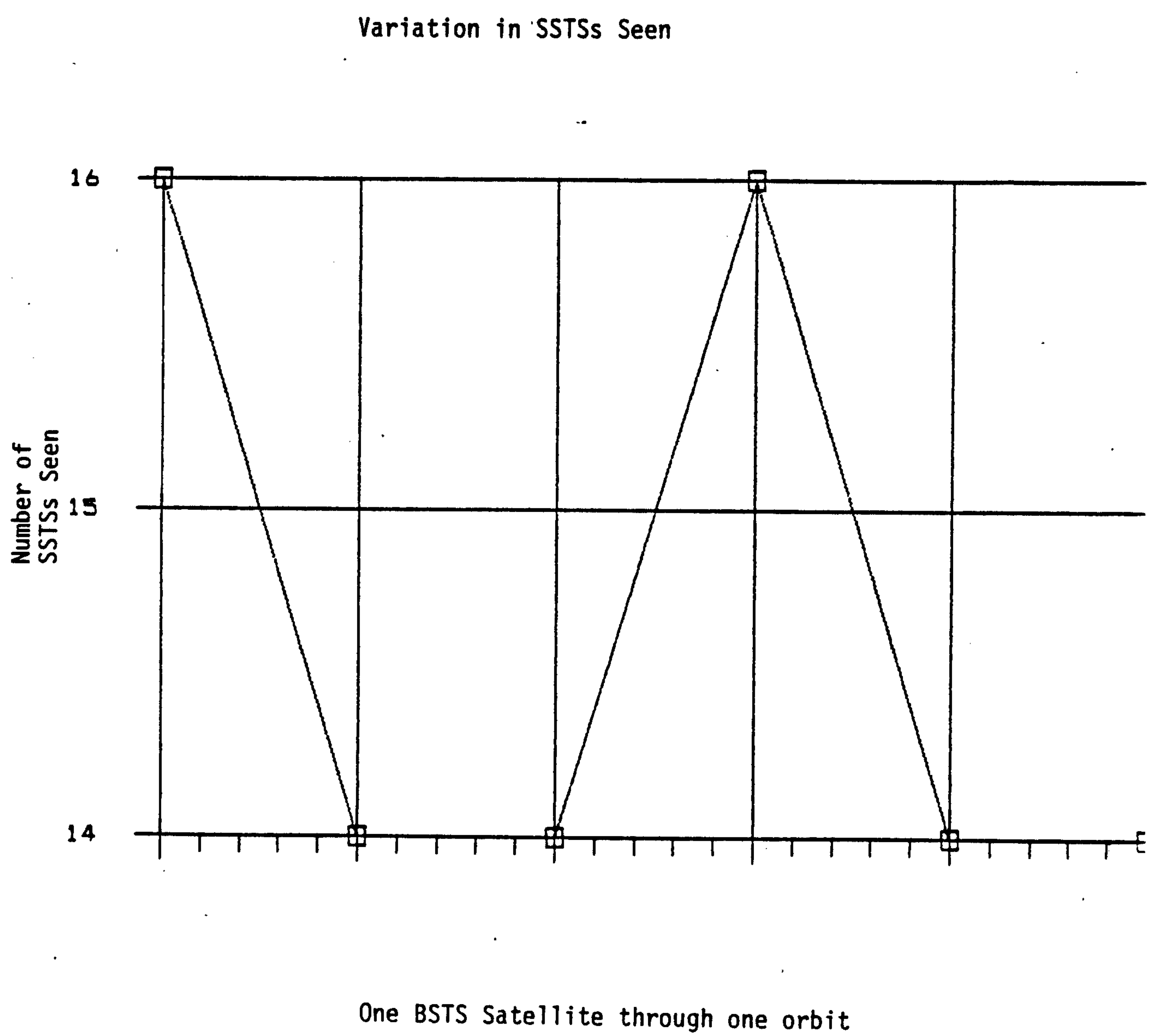


One BSTS through one orbit

BSTS-SSTS Links

Again, depending upon orientation, each BSTS can see 14-16 SSTS satellites. One representative orbit with six points is shown in Figure III-33. The arguments made for the BSTS-CV/SBI links apply with two minor changes: the field of view widens to roughly 21^{o} and the number of links is a little more than an order of magnitude different (190 vs. 15). For purposes here, and using the same antenna system supporting the BSTS-CV/SBI links, nine BSTS-SSTS links will be supported per BSTS satellite. This is an important Phase 2 link and robustness is merited. How nine of the 14-16 are selected depends upon the same concerns expressed in earlier discussions--if nothing else they can be pseudo-randomly selected. Again, all antenna aiming is assumed to be aided with ephemeris information, and all antenna fine calibration is done in space using the SDS constellations which will allow the maximum capability possible. If considered in isolation, lasers could tradeoff reasonably well for this link; however, EHF is probably preferred for the multi-directional, multi-beam BSTS-CV/SBI link, and it would be best to take advantage of the same hardware for these links.

FIGURE III-33



BSTS-BSTS Links

The geometry is obvious, and in a robust architecture, anticipate four BSTS-BSTS links per satellite. This added robustness adds a significant advantage to AJ and BER as shown in Section VII. The data rates are not terribly high and the update rates provide time for parallel connectivity. If the number of BSTS satellites increases beyond the nominal baseline, additional parallel links should be considered. Finally, as with the SSTS<—>SSTS and BSTS<—>SSTS links, in isolation, lasers could tradeoff favorably. But, again, it is probably best to avoid EHF/laser hybrid communication systems (see Section X for further discussion).

IV. DATA RATES AND NUMBERS OF LINKS

DATA RATES AND NUMBERS OF LINKS

From the World Situation Set (Appendix A) it is assumed that the number of objects tracked in the post-boost phase is 3,500 while during midcourse the number could possibly balloon to over 400,000. For purposes here 3,500 and 475,000 will be used. During the SDI Communications Workshop in September 1987, TRW presented analysis supporting a maximum of 235-bit-per-packet data package (the maximum allowable in their link budget) which in actuality contains 193 bits of information including 8 bits for synchronization. In this analysis it is assumed that a 235-bit packet is employed and that as many as 50 bits can be used for synchronization. It is further assumed that the sync bits are distributed throughout the packet so that sync verification is a very high quality estimate of message verification. Further analysis of connectivity probabilities and message quality is covered in Section VII.

The data rate associated with each of the links is dependent on the number of links over which any one satellite is receiving identical information. This is the route diversity concept alluded to earlier. The particular number chosen for any given link is dependent upon the number of different satellites that are in the line of sight of any one satellite as well as on the improvement factor obtainable as discussed in Section VII. The link margins discussed in Section VI have been chosen based on a bit error probability of 10^{-5}. This probability of error is a good compromise as can be seen upon examining the link margins presented in Section VI.

The link redundancy numbers shown in Tables IV-1 thru 5, while not based on an exhaustive analysis, serves as a reasonable initial estimate to examine the advantages of a robust architecture. The redundancy numbers shown range from one to ten depending upon the particular link. Certain links transmit only health and status information which is not as crucial as other links transmitting sensor data, hence redundancy tends to be higher on the latter type of link. Link redundancy is the parameter important to computing the advantage enjoyed by the parallel links described in Section VII.

Now, given the packet size, update rates, number of sensors, and number of objects tracked, we can determine the rates associated with each link. For the BSTS carousel we have, (without TDMA) data rate = 3500 objects x (3 sensors) x 235 bits/sensor/2 second updata rate

= 1.25 MBPS

TDMA data rate = 1.25 MBPS x 4 = 5 MBPS.

Similarly for the SSTS carousel we obtain, (without TDMA) data rate = 475,000 objects x (3 sensors) x 235 bits/sensor x (1.7 growth factor)/10 updata rate = 59.5 MBPS

TDMA data rate = 59.5 Mbs x 4 = 238 MBPS.

Data rates associated with tracking, telemetry, and command (TT&C) links or health and status links utilize the Satellite Data Link Standard (SDLS) rates, nominally 5 KBPS. The remaining data rates shown in Table IV-1 thru 5 are based on results presented at the various Phase 2C architecture conferences and are not derived herein.

Table IV-1

BSTS Transmits TO	Burst RATE (MBPS)	# of Links	Redundancy
BSTS	5	4	N/A
SSTS	1.8	9	N/A
CV/SBI(10 beams)	7.5	15 per beam	N/A
GEP(S)	1.25	1	N/A
GEP(TTC)	.0048	1	N/A
BSTS Receives FROM			
BSTS	5	4	4
SSTS	.015	9	3
CV/SBI	.005	150	3
GEP(S)	N/A	N/A	N/A
GEP(TTC)	.0048	1	1*

* Redundancy not critical

Table IV-2

SSTS Transmits TO	Burst Rate (MBPS)	# of Links	Redundancy
BSTS	.015	3	N/A
SSTS	238	4	N/A
CV/SBI(2 beams)	14	17 per beam	N/A
GEP(S)	238	1	N/A
GEP(TTC)	.0048	1	N/A
SSTS Receives FROM			
BSTS	1.8	3	3
SSTS	238	4	4
CV/SBI	4	34	2
GEP(S)	20	1	1*
GEP(TTC)	.0048	1	1*

*Redundancy Not Critical

Table IV-3

CV/SBI Transmits TO	Burst Rate (MBPS)	# of Links	Redundancy
BSTS	.005	1	N/A
SSTS	4	2	N/A
CV/SBI(2 beams)	4	10	N/A
KKV	.003	10	N/A
CV/SBI Receives FROM			
BSTS	7.5	3	3
SSTS	14	2	2
CV/SBI	4	10	10*
KKV	N/A	N/A	N/A

*Redundancy beyond parallel point-to-point links and the determination of how much relaying should be supported in the architecture is beyond the analysis here. It is possible that when considering BSTS to CV/SBI information (direct, relayed through SSTSs, and relayed through CV/SBIs), the numbers here may provide <u>more</u> redundancy that is needed to insure connectivity. Analysis in this report does show that this much redundancy is probably beyond the point where the marginal utility of additional links is optimized. Therefore, read the number of links and redundancy numbers as containing some margin which can be traded off as necessary to produce a more cost-effective system.

Table IV-4

GSTS Transmits TO	Burst Rate (MBPS)	# of Links	Redundancy
GEP	.0048	1	N/A
CV/SBI	.6	1	N/A
GSTS Receives FROM			
GEP	.0048	1	1
CV/SBI	.6	1	1

Table IV-5

ERIS Transmits TO	Burst Rate (MBPS)	# of Links	Redundancy
GEP	.0048	1	N/A
CV/SBI	.003	1	N/A
ERIS Receives FROM			
GEP	.0048	1	1
CV/SBI	.003	1	1

V . ANTENNA SYSTEM CONSIDERATIONS

ANTENNA SYSTEM CONSIDERATIONS

As discussed in Section X, for the near term EHF, links are preferred primarily due to their technical maturity. Each link will require some type of antenna of which there are currently three choices:

1) Steerable parabolic dish with or without multiple feeds.

2) Waveguide-steerable multiple-beam phased array.

3) Monolithic-steerable multiple-beam phased array.

The communication system architecture described here requires that certain satellites have antenna structures within which multiple independently steerable beams can be formed (e.g., the BSTS to CV/SBI links). If the first approach is selected, for the BSTS satellite, as many as 10 dish antennas (each with a diameter of .7 meters or more) would be mounted on the satellite. Gimbals are required to steer these antennas giving rise to excessive, probably unacceptable, weight (on the order of 350 pounds per antenna). Also, reflector surface smoothness for dish antennas operating at millimeter wave frequencies is an area of concern. For such antennas the gain is reduced as given by:

$$G/G_o \simeq \exp(-\sigma^2/\lambda^2)$$

Where G_o is the ideal gain and G is the actual gain due to an rms surface irregularity of magnitude σ meters.

And, finally, on any satellite system employing sensors, it is certainly preferable to avoid moving masses which will generate perturbations that must be damped out before reaching the sensors.

If this type of antenna system would ever be required, the tradeoff between beamwidth (i.e. number of CV/SBIs illuminated) and total number of beams would have to be revisited. For the architecture described in this report, a better, though riskier in the near term, approach is available, and it is probably preferred.

The second alternative is unrealistic, with the possible exception where one is dealing with a very small number of units, because the requirement for excessively thin waveguide elements, as dictated by the antenna geometry at this frequency, as well as the large number of precisionally-oriented elements, would be labor intensive and extremely expensive. The weight of a reasonably sized array (3500 elements) would also be a concern. The BSTS constellation itself, because of the relatively few satellites, may consider this approach only if no other alternative can be found. Because of the numbers alone, the other satellites cannot possibly employ this technique. And, since the other satellites will require some other antenna system

at this frequency, unless the constellation must be launched early, it is inconceivable that the BSTS could not use the same type of antenna system.

The third alternative is the most viable method, especially for the BSTS to CV/SBI link. Obviously, if this approach is used on any one type of satellite, it may as well be developed for all of them. The primary disadvantage of the monolithic phased array is that the technology is relatively immature. (But, unlike lasercom systems, EHF has only this one area of relatively immature technology, and it is an area where we know how to proceed to gain maturity.) For 60 GHz links, monolithic array antennas (though being built in the laboratory for 20 GHz and 44 GHz antenna systems) are five to ten years away from being incorporated into a space-qualified hardware system. Nonetheless, this is the most promising approach, development is being funded, and hence it has been selected for the architecture described herein. (A better funded development program could make the technology available sooner, and consideration should be given to put more emphasis in this area.)

Finally, a few words need to be written on null-steering possibilities. For any properly-designed, phased-array antenna system, one or more nulls can be steered with the addition of another receiver and more processing.* Where jammers are

*See <u>Coherent Sidelobe Cancelling</u> by Peterson and Weiss, J. Appl. Phys., 1 August 1984.

employed on satellites, their ephemeris information can be used to help steer the nulls. The inclusion of a single null on any SDS satellite makes an already "near impossible" jamming problem at least twice as hard. However, there is another advantage gained from nulling: The processing link budgets (inherent in the data and bandwidth numbers) of Section VI can be relaxed, or the advantage offered by nulling can be used to offset any of the other parameters comprising of the total link margin. Note that this is another situation where a "good guy/bad guy" dB tradeoff has meaning well beyond the number of decibels--here an additional receiver and some processing would have to be negated with "jamming geometry," that is, more satellites at different angles. It is inconceivable that an adversary would waste so much in resources for so little gain. Nulling should be considered to enhance link margins beyond what is shown in Section VI.

VI. MARGIN ANALYSIS

MARGIN ANALYSIS

The EW threat consists of airborne, ship, and spaceborne jammers. The spaceborne jammers have been set at 36 by the WSS, with 6 allocated by us here to the same orbit as the BSTS satellites while the remaining 30 have been placed in the same orbital planes as the SSTS satellites but at an altitude midway between the SSTS and CV/SBI constellations. The spaceborne jammers have been restricted to a 5-2 KW output power level while the ground-based jammers are capable of 200 KW. Each of the jammers in the SSTS orbital plane is assumed to be equipped with 2 phased array antennas capable of multi-beam propagation. Thus, any one jammer can simultaneously jam 10 CV/SBI and 2 SSTS satellites.

Table VI-1 shows the required E_B/No ratios for the various types of links imposed by the threat environment and the system architecture. Table VI-2 identifies which channel type each of the SDS links are associated with while Table VI-3 summarizes the required data rates. The nuclear effect parameters are itemized in Table VI-4. These parameters are based on a multiple burst DNA model which is discussed in Appendix B.

TABLE VI-1

	Required Eb/No
1. LOS/Coherent Broadband Jamming	4.5 dB
2. LOS/Non-Coherent Multi-tone Jamming	10.0 dB
3. LOS/Scintillation Coherent Broadband Jamming	7.0 dB
4. LOS/Scintillation Non-Coherent Broadband Jamming	10.0 dB

TABLE VI-2

LOS/Coherent Broadband Jamming	BSTS to BSTS SSTS SSTS to SSTS
LOS/Non-Coherent Multi-tone Jamming	SSTS to BSTS
LOS/Scintillation/Coherent Broadband Jamming	BSTS to CV GEP SSTS to CV GEP CV to CV
LOS/Scintillation/Non-Coherent Broadband Jamming	CV to BSTS GEP to BSTS

TABLE VI-3
DATA RATES IN MB/S

	RECEIVER			
	BSTS	SSTS	CV	GEP
Transmitter				
BSTS	5	1.8	7.5	1.25
SSTS	0.015	238	14	20
CV	0.005	4	4	0.005
GEP	0.005	20	0.005	-

TABLE VI-4
SCINTILLATION PARAMETERS

	Ground-to-Space Links	Space to Space Links
τ_o	0.04 mS	0.08 mS
fo	2.6 MHz	41 MHz
2 d_{rms}	122 nS	7.8 nS
Antenna Loss	21.1 dB	15.1 dB
Absorption	4.8 dB	1.1 dB
Temp	8900° K	4000° K

The following tables show the various link margins for the following cases:

1) No jamming, no nuclear burst.
2) No nuclear burst.
3) Margins without multiple links.
4) Margins with five parallel links.

The transmitter power levels and antenna gains have been selected to be commensurate with monolithic array technology as well as to provide slightly positive link margins for the third case above (there is only one exception to the positive margin result).

Tables VI-5 through VI-8 contain the link margins where there is no jamming present, no nuclear threat, and only one link, i.e. case (1) above. As noted, all links have positive margins, several of them substantial.

The results in each table presented herein are based on a bit error probability of 10^{-5} as discussed in Appendix B. Also per the Appendix, a processing gain produced by a spread bandwidth equivalent to 10% of the carrier frequency has been assumed for all links.

TABLE VI-5
TRANSMITTER B

Receiver	B	S	C	G
Distance (Km)	73000(Max)	48000(Max)	44000(Max)	34000(Min)
Data Rate (KBPS)	5000	1800	7500	1250
Frequency (GHz)	60	60	60	20
Power (dBm)	50	40	40	50
X/Ant Gain (dB)	50	45	50	50
Xmit Loss (dB)	2	2	2	2
R/Ant Gain (dB)	50	45	50	60
RCV Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
T (^{o}K)	1000	1000	1000	1000
EB/NO (dB)	22.3	30.4	14.9	54.9
EB/NJ (dB)	N/A	N/A	N/A	N/A
EB/NT (dB)	22.3	30.4	14.9	54.9
Req'd EB/NT (dB)	4.5	4.5	7	7
Margin (dB)	17.8	25.9	7.9	47.9

TABLE VI-6
TRANSMITTER S

Receiver	B	S	C	G
Distance (Km)	48000(Max)	12900(Max)	9100(Max)	3000(Min)
Data Rate (KBPS)	15	238000	14000	238000
Frequency (GHz)	60	60	60	20
Power (dBm)	40	50	47	50
X/Ant Gain (dB)	40	50	50	50
Xmit Loss (dB)	2	2	2	2
R/Ant Gain (dB)	40	50	50	50
RCV Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
T (^{o}K)	1000	1000	1000	1000
EB/NO (dB)	21.2	20.6	29.9	53.6
EB/NJ (dB)	N/A	N/A	N/A	N/A
EB/NT (dB)	21.2	20.6	29.9	53.6
Req'd EB/NT (dB)	4.5	4.5	7	7
Margin (dB)	16.7	16.1	22.9	46.8

TABLE VI-7
TRANSMITTER C

Receiver	B	S	C	G
Distance (Km)	44000 (Max)	9100 (Max)	4600 (Max)	500 (Min)
Data Rate (KBPS)	5	4000	4000	5
Frequency (GHz)	60	60	60	20
Power (dBm)	45	45	45	25
X/Ant Gain (dB)	40	47.5	45	35
Xmit Loss (dB)	2	2	2	2
R/Ant Gain (dB)	40	47.5	45	35
RCV Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
T (^{O}K)	1000	1000	1000	1000
EB/NO (dB)	31.7	31.4	32.3	50.2
EB/NJ (dB)	N/A	N/A	N/A	N/A
EB/NT (dB)	31.7	31.4	32.3	50.2
Req'd EB/NT (dB)	4.5	4.5	7	7
Margin (dB)	27.2	26.9	25.3	43.2

TABLE VI-8
TRANSMITTER G

Receiver	B	S	C
Distance (Km)	34000 (Min)	3000 (Min)	500 (Min)
Data Rate (KBPS)	5	20000	5
Frequency (GHz)	44	44	44
Power (dBm)	38	43	27
X/Ant Gain (dB)	38.8	43.8	27.8
Xmit Loss (dB)	2	2	2
R/Ant Gain (dB)	43	48	32
RCV Loss (dB)	2	2	2
Scatter Loss (dB)	0	0	0
Absorption (dB)	0	0	0
T (^{o}K)	1000	1000	1000
EB/NO (dB)	31.4	31.9	35.1
EB/NJ (dB)	N/A	N/A	N/A
EB/NT (dB)	31.4	31.9	35.1
Req'd EB/NT (dB)	4.5	4.5	7
Margin (dB)	26.9	27.4	28.1

Tables VI-9 through VI-12 show link margins when jamming is present with no nuclear threat, i.e. case (2) above. Note all links have positive margins except the BSTS to GEP link where there is zero margin. With the nuclear environment added, this particular link is actually better due to the attenuation experienced by the jammer.

TABLE VI-9
TRANSMITTER B

Receiver	B	S	C	G
Distance (Km)	73000 (Max)	48000 (Max)	44000 (Max)	34000 (Min)
Data Rate (KBPS)	5000	1800	7500	1250
Frequency (GHz)	60	60	60	20
Power (dBm)	50	40	40	50
X/Ant Gain (dB)	50	45	50	5-
Xmit Loss (dB)	2	2	2	2
R/Ant Gain (dB)	50	45	50	60
RCV Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
T (^{o}K)	1000	1000	1000	1000
EB/NO (dB)	22.3	30.4	14.9	44.5
EB/NJ (dB)	11.3	30.2	12.7	7.0
EB/NT (dB)	11.0	27.3	10.7	2.0
Req'd EB/NT (dB)	4.5	4.5	7	7
Margin (dB)	6.5	2.8	3.7	0

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	-166.4	-121.1

TABLE VI-10
TRANSMITTER S

Receiver	B		S		C		G	
Distance (Km)	48000	(Max)	12900	(Max)	9100	(Max)	3000	(Min)
Data Rate (KBPS)	15		238000		14000		238000	
Frequency (GHz)	60		60		60		20	
Power (dBm)	40		50		47		50	
X/Ant Gain (dB)	40		50		50		50	
Xmit Loss (dB)	2		2		2		2	
R/Ant Gain (dB)	40		50		50		50	
RCV Loss (dB)	2		2		2		2	
Scatter Loss (dB)	0		0		0		0	
Absorption (dB)	0		0		0		0	
T (^{o}K)	1000		1000		1000		1000	
EB/NO (dB)	21.2		20.6		29.9		53.6	
EB/NJ (dB)	10.2		20.4		27.8		21.7	
EB/NT (dB)	9.9		17.5		29.9		21.7	
Req'd EB/NT (dB)	4.5		4.5		7		7	
Margin (dB)	5.4		13.0		22.7		21.7	

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	-166.4	-121.1

TABLE VI-11
TRANSMITTER C

Receiver	B		S		C		G	
Distance (Km)	44000	(Max)	9100	(Max)	4600	(Max)	500	(Min)
Data Rate (KBPS)	5		4000		4000		5	
Frequency (GHz)	60		60		60		20	
Power (dBm)	45		45		45		25	
X/Ant Gain (dB)	40		47.5		45		35	
Xmit Loss (dB)	2		2		2		2	
R/Ant Gain (dB)	40		47.5		45		35	
RCV Loss (dB)	2		2		2		2	
Scatter Loss (dB)	0		0		0		0	
Absorption (dB)	0		0		0		0	
T (^{o}K)	1000		1000		1000		1000	
EB/NO (dB)	31.7		38.4		32.3		50.2	
EB/NJ (dB)	20.7		31.2		30.1		39.1	
EB/NT (dB)	20.4		28.3		28.1		38.8	
Req'd EB/NT (dB)	4.5		4.5		7		7	
Margin (dB)	15.9		23.8		21.1		31.8	

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	0	0
Absorption (dB)	0	0	0	0
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	166.4	-121.1

TABLE VI-12
TRANSMITTER G

Receiver	B		S		C	
Distance (Km)	34000	(Min)	3000	(Min)	500	(Min)
Data Rate (KBPS)	5		20000		5	
Frequency (GHz)	44		44		44	
Power (dBm)	38		43		27	
X/Ant Gain (dB)	38.8		43.8		27.8	
Xmit Loss (dB)	2		2		2	
R/Ant Gain (dB)	43		48		32	
RCV Loss (dB)	2		2		2	
Scatter Loss (dB)	0		0		0	
Absorption (dB)	0		0		0	
T (^{o}K)	1000		1000		1000	
EB/NO (dB)	31.4		31.5		35.1	
EB/NJ (dB)	1000		17.2		1000	
EB/NT (dB)	31.4		17.0		35.1	
Req'd EB/NT (dB)	4.5		4.5		7	
Margin (dB)	26.9		12.5		28.1	

JAMMER

Receiver	S
Distance (Km)	2000
Bandwidth (GHz)	4.4
Frequency (GHz)	44
Power (dBm)	62.4
X/Ant Gain (dB)	55
Xmit Loss (dB)	2
Scatter Loss (dB)	0
Absorption (dB)	0
Sidelobe (dB)	-35
Null Depth (dB)	0
J Density (dBm/Hz)	-154.4

Tables VI-13 through VI-16 show link margins for the case where both jamming as well as nuclear scintillations are present, however, only a single link margin is calculated here; i.e. case (3) above. As noted, all links have positive margin with the exception of the BSTS to CV link. The nuclear environment is the cause of this difficulty and may be circumvented by relaying the information through a less-perturbed link (use the robustness), by increasing the transmitted power or the size of the antenna by narrowing the antenna beamwidth further, and/or utilizing more processing on the BSTS satellite to lower the data rate. Multiple parallel links are built into the discussion of this report, so any one link breaking connectivity does not prohibit the information from being communicated as long as care is taken to judiciously choose the multiple CV/SBI-CV/SBI relay links to insure that the same nuclear event cannot break all linkages among several CV/SBI satellites. Increasing power is purely a function of cost as is antenna sizing--3 to 5 dB advantage for each is possible. Antenna beamwidth can be reduced for another 4 dB improvement, but again the cost increases. In each of these cases the RF section and/or antenna system cost will increase (roughly) linearly with the improvement. The additional BSTS processing can yield up to about 7 dB margin, while the cost should not increase too dramatically, since margin is already built into its assumed capability. But, none of these possible improvements in link margin is either recommended or deemed necessary. An appropriate selection of multiple routes or multiple routing schemes, in the case of pseudo-random

selections, is considered capable of closing the link. The underlying concept needs to be that if any BSTS-CV/SBI or SSTS-CV/SBI link is connected then, except for those CV/SBIs extremely close to a nuclear event (where survivability of the CV/SBI may be questioned), the information will permeate the CV/SBI constellation.

TABLE VI-13
TRANSMITTER B

Receiver	B	S	C	G
Distance (Km)	73000 (Max)	48000 (Max)	44000 (Max)	34000 (Min)
Data Rate (KBPS)	5000	1800	7500	1250
Frequency (GHz)	60	60	60	20
Power (dBm)	50	40	40	50
X/Ant Gain (dB)	50	45	50	50
Xmit Loss (dB)	2	2	2	2
R/Ant Gain (dB)	50	45	50	60
RCV Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	15.1	21.1
Absorption (dB)	0	0	1.1	4.8
T (^{o}K)	1000	1000	4000	8900
EB/NO (dB)	22.3	30.4	-7.3	19.1
EB/NJ (dB)	11.3	30.2	28.9	32.9
EB/NT (dB)	11.0	27.3	-7.3	18.9
Req'd EB/NT (dB)	4.5	4.5	7	7
Margin (dB)	6.5	2.8	-14.3*	11.9

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	15.1	21.1
Absorption (dB)	0	0	1.1	4.8
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	-182.6	-147.0

*Read discussion on how this link can be closed.

TABLE VI-14
TRANSMITTER S

Receiver	B		S		C		G	
Distance (Km)	48000	(Max)	12900	(Max)	9100	(Max)	3000	(Min)
Data Rate (KBPS)	15		238000		14000		238000	
Frequency (GHz)	60		60		60		20	
Power (dBm)	40		50		47		50	
X/Ant Gain (dB)	40		50		50		50	
Xmit Loss (dB)	2		2		2		2	
R/Ant Gain (dB)	40		50		50		50	
RCV Loss (dB)	2		2		2		2	
Scatter Loss (dB)	0		0		15.1		21.1	
Absorption (dB)	0		0		1.1		4.8	
T (^{o}K)	1000		1000		4000		8900	
EB/NO (dB)	21.2		20.6		7.7		18.2	
EB/NJ (dB)	10.2		20.4		43.9		21.7	
EB/NT (dB)	9.9		17.5		7.7		16.6	
Req'd EB/NT (dB)	4.5		4.5		7		7	
Margin (dB)	5.4		13.0		.7		9.6	

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	15.1	21.1
Absorption (dB)	0	0	1.1	4.8
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	-182.6	-147.0

TABLE VI-15
TRANSMITTER C

Receiver	B		S		C		G	
Distance (Km)	44000	(Max)	9100	(Max)	4600	(Max)	500	(Min)
Data Rate (KBPS)	5		4000		4000		5	
Frequency (GHz)	60		60		60		20	
Power (dBm)	45		45		45		25	
X/Ant Gain (dB)	40		47.5		45		35	
Xmit Loss (dB)	2		2		2		2	
R/Ant Gain (dB)	40		47.5		45		35	
RCV Loss (dB)	2		2		2		2	
Scatter Loss (dB)	15.1		15.1		15.1		21.1	
Absorption (dB)	1.1		1.1		1.1		4.8	
T (^{o}K)	4000		4000		4000		8900	
EB/NO (dB)	9.5		9.2		10.1		14.8	
EB/NJ (dB)	36.9		47.4		46.3		65.0	
EB/NT (dB)	9.5		9.2		10.1		14.8	
Req'd EB/NT (dB)	5.0		4.7		3.1		6.8	
Margin (dB)	30.0		14.7		18.1		81.8	

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	15.1	15.1	15.1	21.1
Absorption (dB)	1.1	1.1	1.1	4.8
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-173.8	-184.6	82.6	-147.0

TABLE VI-16
TRANSMITTER G

Receiver	B	S	C
Distance (Km)	34000 (Min)	3000 (Min)	500 (Min)
Data Rate (KBPS)	5	20000	5
Frequency (GHz)	44	44	44
Power (dBm)	38	43	27
X/Ant Gain (dB)	38.8	43.8	27.8
Xmit Loss (dB)	2	2	2
R/Ant Gain (dB)	43	48	32
RCV Loss (dB)	2	2	2
Scatter Loss (dB)	15.1	15.1	15.1
Absorption (dB)	1.1	1.1	1.1
T (^{o}K)	4000	4000	4000
EB/NO (dB)	9.2	9.3	12.9
EB/NJ (dB)	1000	33.4	1000
EB/NT (dB)	9.2	9.3	12.9
Req'd EB/NT (dB)	4.5	4.5	7
Margin (dB)	4.7	4.8	5.9

JAMMER

Receiver	S
Distance (KM)	2000
Bandwidth (GHz)	4.4
Frequency (GHz)	44
Power (dBM)	62.4
X/Ant Gain (dB)	55
Xmit Loss (dB)	2
Scatter Loss (dB)	15.1
Absorption (dB)	1.1
Sidelobe (dB)	-35
Null Depth (dB)	0
J Density (dBm/Hz)	-170.6

Tables VI-17 through VI-20 contain link margins for the case when jamming is present as well as the nuclear threat but assumes five parallel links are present in each case (case 4 above). Five parallel links result in a 4-5 dB reduction in the required Eb/N_T ratio thus improving all link margins by 4.6 dB. But, again, bear in mind, this improvement is a spatial improvement and though it can be numerically expressed, in reality in most instances when the favorable geometry can be and is selected, the effect can be tantamount to eliminating the jammer and the nuclear interference. Where the geometry is unfavorable or not exploited, it may add no margin. The geometry here is so vast and so robust, the only question is determining how best to exploit it.

TABLE VI-17
TRANSMITTER B

Receiver	B	S	C	G
Distance (Km)	73000 (Max)	48000 (Max)	44000 (Max)	34000 (Min)
Data Rate (KBPS)	5000	1800	7500	1250
Frequency (GHz)	60	60	60	20
Power (dBm)	50	40	40	50
X/Ant Gain (dB)	50	45	50	50
Xmit Loss (dB)	2	2	2	2
R/Ant Gain (dB)	50	45	50	60
RCV Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	15.1	21.1
Absorption (dB)	0	0	1.1	4.8
T (^{o}K)	1000	1000	4000	8900
EB/NO (dB)	22.3	30.4	-7.3	9.1
EB/NJ (dB)	11.3	30.2	28.9	22.9
EB/NT (dB)	11.0	27.3	-7.3	8.9
Req'd EB/NT (dB)	-.1	-.1	2.4	2.4
Margin (dB)	11.1	27.4	-9.7*	6.5

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	15.1	21.1
Absorption (dB)	0	0	1.1	4.8
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	-182.6	-147.0

*Read discussion on how this link can be closed.

TABLE VI-18
TRANSMITTER S

Receiver	B		S		C		G	
Distance (Km)	48000	(Max)	12900	(Max)	9100	(Max)	3000	(Min)
Data Rate (KBPS)	15		238000		14000		238000	
Frequency (GHz)	60		60		60		20	
Power (dBm)	40		50		47		50	
X/Ant Gain (dB)	40		50		50		50	
Xmit Loss (dB)	2		2		2		2	
R/Ant Gain (dB)	40		50		50		50	
RCV Loss (dB)	2		2		2		2	
Scatter Loss (dB)	0		0		15.1		21.1	
Absorption (dB)	0		0		1.1		4.8	
T (^oK)	1000		1000		4000		8900	
EB/NO (dB)	21.2		20.6		7.7		18.2	
EB/NJ (dB)	10.2		20.4		43.9		21.7	
EB/NT (dB)	9.9		17.5		7.7		16.6	
Req'd EB/NT (dB)	-.1		-.1		2.4		2.4	
Margin (dB)	10.0		17.6		5.3		14.2	

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	0	0	15.1	21.1
Absorption (dB)	0	0	1.1	4.8
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-157.6	-168.4	-182.6	-147.0

TABLE VI-19
TRANSMITTER C

Receiver	B		S		C		G	
Distance (Km)	44000	(Max)	9100	(Max)	4600	(Max)	500	(Min)
Data Rate (KBPS)	5		4000		4000		5	
Frequency (GHz)	60		60		60		20	
Power (dBm)	45		45		45		25	
X/Ant Gain (dB)	40		47.5		45		35	
Xmit Loss (dB)	2		2		2		2	
R/Ant Gain (dB)	40		47.5		45		35	
RCV Loss (dB)	2		2		2		2	
Scatter Loss (dB)	15.1		15.1		15.1		21.1	
Absorption (dB)	1.1		1.1		1.1		4.8	
T (^{O}K)	4000		4000		4000		8900	
EB/NO (dB)	9.5		9.2		10.1		14.8	
EB/NJ (dB)	36.9		47.4		46.3		65.0	
EB/NT (dB)	9.5		9.2		10.1		14.8	
Req'd EB/NT (dB)	-.1		-.1		2.4		2.4	
Margin (dB)	9.6		9.3		7.7		12.4	

JAMMER

Receiver	B	S	C	G
Distance (Km)	1000	2000	500	1000
Bandwidth (GHz)	6	6	6	2
Frequency (GHz)	60	60	60	20
Power (dBm)	67.2	62.4	52.4	83
X/Ant Gain (dB)	50	50	50	46.4
Xmit Loss (dB)	2	2	2	2
Scatter Loss (dB)	15.1	15.1	15.1	21.1
Absorption (dB)	1.1	1.1	1.1	4.8
Sidelobe (dB)	-35	-35	-35	-35
Null Depth (dB)	0	0	0	0
J Density(dBm/Hz)	-173.8	-184.6	82.6	-147.0

TABLE VI-20
TRANSMITTER G

Receiver	B		S		C	
Distance (Km)	34000	(Min)	3000	(Min)	500	(Min)
Data Rate (KBPS)	5		20000		5	
Frequency (GHz)	44		44		44	
Power (dBm)	38		43		27	
X/Ant Gain (dB)	38.8		43.8		27.8	
Xmit Loss (dB)	2		2		2	
R/Ant Gain (dB)	43		48		32	
RCV Loss (dB)	2		2		2	
Scatter Loss (dB)	15.1		15.1		15.1	
Absorption (dB)	1.1		1.1		1.1	
T (^{o}K)	4000		4000		4000	
EB/NO (dB)	9.2		9.3		12.9	
EB/NJ (dB)	1000		33.4		1000	
EB/NT (dB)	9.2		33.4		12.9	
Req'd EB/NT (dB)	-.1		-.1		2.4	
Margin (dB)	9.3		9.4		10.5	

JAMMER

Receiver	S
Distance (Km)	2000
Bandwidth (GHz)	4.4
Frequency (GHz)	44
Power (dBm)	62.4
X/Ant Gain (dB)	55
Xmit Loss (dB)	2
Scatter Loss (dB)	15.1
Absorption (dB)	1.1
Sidelobe (dB)	-35
Null Depth (dB)	0
J Density (dBm/Hz)	-170.6

VII. DIVERSE GEOMETRY/PARALLEL LINK ANALYSIS

DIVERSE GEOMETRY, PARALLEL LINK ANALYSIS

The questions naturally arise: Can the real advantage of geometrically-robust, parallel-link architecture be explained and can the advantage be specified numerically? The answer to both questions is yes. Of course analysis to support the answer can be made very complex; however, in this instance, it can also be made considerably less complex by thinking it through with a firm grip on the angular diversity shown in Section III and with an appreciation for the vast distances involved in the SDS constellations. If any node-to-node link can be closed where there is no jamming and no nuclear scintillations and spatially diverse alternate, parallel links are available, then connectivity is maintained in the presence of jamming/scintillations except when <u>all</u> the available routings are disrupted. All routings, jamming interference, and nuclear interference are spatial in nature and to equate the sum total to a simplified "dB link margin" analysis is both all that can be completed within the scope and resources of this particular effort and, through nominally correct, somewhat misleading in its numerical simplicity. For example, an additional 3 dB of margin can mean twice as much power, a narrower beamwidth, closer nodes, or . . . in a spatial sense, could mean an adversary would need twice as many angular orientations (i.e. twice a many constellations of jammers) for equal effectiveness. This spatial angular diversity is the key exploitable link for maintaining connectivity for a system as spatially robust as SDS. Jamming

and/or scintillations would have to be intense to the degree where the node's survival would be in jeopardy to effectively deprive it of all available angular connectivity.

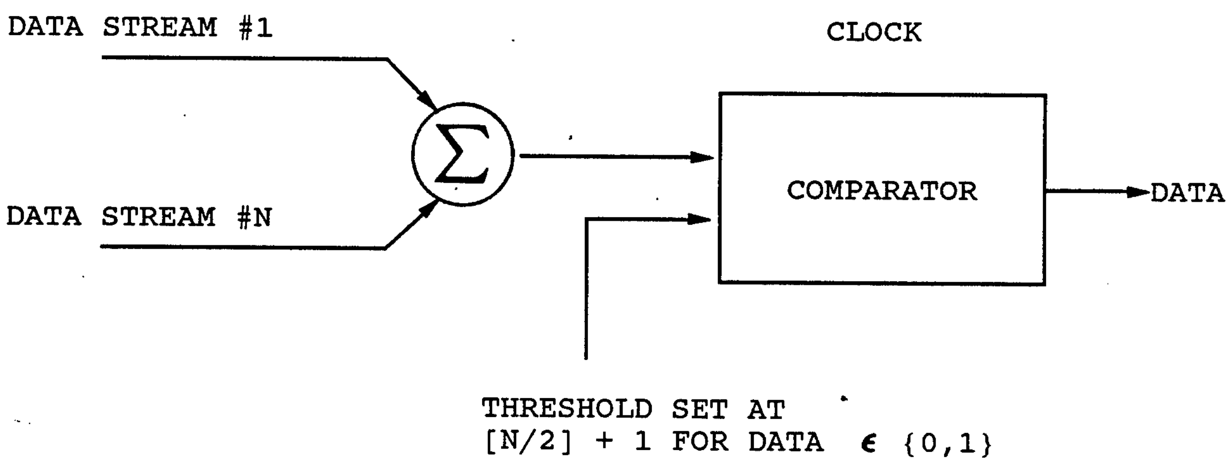
An analysis to numerically calculate the specific link margin advantage of a truly robust geometry with many parallel links as described in Section III should be taken well beyond the numerical analysis presented in the remainder of this section. It would have to make alternative proposals as to which of the available parallel links would be used. Jamming and nuclear scintillation scenarios would need to be modeled, and an heuristic, iterative process would yield a valid baseline scheme. The specific multiple-link analysis could then determine the specific link margin for each parallel link for each of several typical hostile scenarios and the overall link margin can then be calculated. Even without the investment in such an analysis, a simple reference to the benign, then the jammed, then the scintillated, then the combined jammed/scintillated margin analysis while remembering the geometry easily allows one to leap to the conclusion that with a moderate amount of parallelism, connectivity is assured.

Now a first order numerical analysis is shown beginning with an understanding from the geometrics presented in Section III.
In every instance there is sufficient geometric diversity to support the contention that for the number of links chosen between any two nodes, spatial independence can be maintained

(e.g. When selecting which CV/SBIs talk to one another, a choice can be made which assures that only one will be within a single beamwidth for any one transmission burst.). Furthermore, if any question of spatial independence remains, the temporal diversity from the multiplexing adds another layer of independence. Therefore, the autocorrelation propagation noise between any two links is essentially zero.

Prior to discussing specific techniques to process data bits to obtain the benefits inherent in route diversity, we will discuss majority logic decision processing and show how this in effect improves bit error probabilities. Majority logic decision processing is utilized in each of two different data bit processing approaches which will be discussed subsequently.

Figure VII-1 illustrates the majority logic decision process for N routes, i.e. N different bit streams each supposedly carrying identical data. Suppose that each of the N-bit streams have identical bit error probabilities P_e (this assumption may not be met in practice but serves to illustrate the improvement route diversity provides), then the probability that one of the output data bits of Figure VII-1 is in error, P_e, is simply the probability that [N/2] + 1 of that input data streams have bits in error at the clock sampling instant. Since each data stream is independent,



NOTE: [ ] DENOTES THE GREATEST INTEGER FUNCTION.

FIGURE VII-1

$$P_e = 1 - P\,([N/2] + 1 \text{ or more bits are correct}) =$$

$$1 - \sum^{N} \binom{N}{k} (1 - p_e)^{k}\, p_e^{(N-k)}$$

$$= \sum_{k=0}^{[N/2]} \binom{N}{k} (1 - p_e)^{k}\, p_e^{(N-k)}$$

since it can easily be shown that

$$1 = \sum_{k=0}^{N} \binom{N}{k} (1 - p_e)^{k}\, p_e^{(N-k)} \quad .$$

The resulting bit error probability P_e is shown in Tables VII-1 to 5 for different values of p_e and $1 \leq N \leq 127$, N odd. Also shown in these tables is the improvement in signal-to-noise ratio, E_b/N_o, over the E_b/N_o required of a single link to obtain the bit error probability P_e for non-coherent FSK demodulation. Figures VII-2 through 6 show graphically the decibel improvement in E_b/N_o as N ranges from 1 to 127. Figure VII-7 shows the improvement in bit error probability due to route diversity when majority logic decision processing is used for N = 1, 3, 5, 7.

TABLE VII-1

E_b/N_0 = 5.08 dB

N	Pe	dB Improvement
1	.10000000000000D+00	.00000000000000
3	.28000000000000D-01	2.53080546855927
5	.85600000000000D-02	4.02654141187668
7	.27280000000000D-02	5.10250151157379
9	.89092000000000D-03	5.94736933708191
11	.29570608000000D-03	6.64489686489105
13	.99285486400000D-04	7.23987758159638
15	.33624887968000D-04	7.75917887687683
17	.11464435997200D-04	8.22023630142212
19	.39298823271280D-05	8.63502323627472
21	.13530649719634D-05	9.01213467121124
23	.46757682627953D-06	9.35795187950134
25	.16208341601861D-06	9.67734694480896
27	.56335697082132D-07	9.97412919998169
29	.19626131794185D-07	10.25133132934570
31	.68512030739788D-08	10.51140904426575
33	.23959466828070D-08	10.75638294219971
35	.83922768495056D-09	10.98793029785156
37	.29437603570079D-09	11.20746374130249
39	.10339119443745D-09	11.41618013381958
41	.36355515154017D-10	11.61510825157166
43	.12797262148697D-10	11.80513381958008
45	.45090404095519D-11	11.98702692985535
47	.15901449275053D-11	12.16146111488342
49	.56123427008392D-12	12.32903003692627
51	.19823459014564D-12	12.49025821685791
53	.70067780075127D-13	12.64561176300049
55	.24782173850212D-13	12.79550790786743
57	.87704773635452D-14	12.94031977653503
59	.31056495720556D-14	13.08038234710693
61	.11003005338683D-14	13.21600079536438
63	.39001884227808D-15	13.34745168685913
65	.13831276782080D-15	13.47498178482056
67	.49071523240490D-16	13.59882354736328
69	.17417128839357D-16	13.71918320655823
71	.61843408832975D-17	13.83625388145447
73	.21967011588964D-17	13.95021080970764
75	.78055018650104D-18	14.06121730804443
77	.27744391999215D-18	14.16942238807678
79	.98647692971298D-19	14.27496433258057
81	.35085634265385D-19	14.37797307968140
83	.12482346071916D-19	14.47856783866882
85	.44420335573825D-20	14.57685947418213
87	.15811781743041D-20	14.67295050621033
89	.56297373569036D-21	14.76693987846375
91	.20049295554386D-21	14.85891699790955
93	.71418277743864D-22	14.94896650314331
95	.25445722289143D-22	15.03716945648193
97	.90679994083982D-23	15.12359738349915
99	.32321822349738D-23	15.20832300186157
101	.11522969943653D-23	15.29141306877136
103	.41087907918366D-24	15.37292718887329
105	.14653507634775D-24	15.45292615890503

TABLE VII-1 (Contd.)

107	.52269007411926D-25	15.53146481513977
109	.18647442824815D-25	15.60859680175781
111	.66537137848318D-26	15.68436980247498
113	.23745226023519D-26	15.75883388519287
115	.84752701197219D-27	15.83203077316284
117	.30254755126772D-27	15.90400457382202
119	.10801759461626D-27	15.97479581832886
121	.38570400091689D-28	16.04444265365601
123	.13774336210621D-28	16.11298084259033
125	.49197417859943D-29	16.18044734001160
127	.17573866343420D-29	16.24687194824219

TABLE VII-2

E_b/N_o = 8.93 dB

N	Pe	dB Improvement
1	.10000000000000D-01	.00000000000000
3	.29800000000000D-03	2.78310865163803
5	.98506000000000D-05	4.42420750856400
7	.34166980000000D-06	5.59772968292236
9	.12185368570000D-07	6.51377618312836
11	.44254343383480D-09	7.26607501506805
13	.16278881392003D-10	7.90479838848114
15	.60452484932097D-12	8.46001505851746
17	.22614362673891D-13	8.95119369029999
19	.85091047329055D-15	9.39167916774750
21	.32169401503951D-16	9.79102075099945
23	.12209889904170D-17	10.15629291534424
25	.46496735528439D-19	10.49288392066956
27	.17756842846041D-20	10.80499172210693
29	.67978999250222D-22	11.09595417976379
31	.26080409268757D-23	11.36846780776978
33	.10024753819636D-24	11.62474274635315
35	.38597617161819D-26	11.86661243438721
37	.14883232169483D-27	12.09561705589294
39	.57466967263472D-29	12.31306076049805
41	.22216074631409D-30	12.52005934715271
43	.85979697145185D-32	12.71757364273071
45	.33309026011526D-33	12.90643692016602
47	.12916016903379D-34	13.08737754821777
49	.50126062283819D-36	13.26103568077087
51	.19468761102962D-37	13.42797756195068
53	.75670641141438D-39	13.58870267868042
55	.29431219069577D-40	13.74366044998169
57	.11454089101670D-41	13.89325141906738
59	.44603208583829D-43	14.03783440589905
61	.17378345641816D-44	14.17773604393005
63	.67744282216084D-46	14.31324958801270
65	.26420754122169D-47	14.44464445114136
67	.10308934686610D-48	14.57216262817383
69	.40240846809747D-50	14.69602584838867
71	.15714293247982D-51	14.81644034385681
73	.61388572010923D-53	14.93359327316284
75	.23990340628497D-54	15.04765510559082
77	.93785014089485D-56	15.15878677368164
79	.36675089679497D-57	15.26713490486145
81	.14346393017207D-58	15.37283539772034
83	.56136025723641D-60	15.47601580619812
85	.21971618242723D-61	15.57679176330566
87	.86019779094671D-63	15.67527413368225
89	.33685680259675D-64	15.77156662940979
91	.13194660051710D-65	15.86576223373413
93	.51695465089167D-67	15.95795154571533
95	.20258337592360D-68	16.04821920394897
97	.79405081494342D-70	16.13664269447327
99	.31130219337164D-71	16.22329592704773
101	.12206803070165D-72	16.30824923515320
103	.47874500104988D-74	16.39156699180603
105	.18779585162298D-75	16.47331237792969

TABLE VII-2 (Contd.)

107	.736790829650790-77	16.55354261398315
109	.28911865333281D-78	16.63231492042542
111	.11346947734614D-79	16.70967817306519
113	.44540033169113D-81	16.78568482398987
115	.17485907843750D-82	16.86038017272949
117	.68657779029300D-84	16.93380951881409
119	.26962061448296D-85	17.00601458549500
121	.10589517765645D-86	17.07703590393066
123	.41596528178716D-88	17.14691162109375
125	.16341576638971D-89	17.21567749977112
127	.64207393672074D-91	17.28337049484253

TABLE VII-3

E_b/N_0 = 10.94 dB

N	Pe	dB Improvement
1	.10000000000000D-02	.00000000000000
3	.29980000000000D-05	2.86650329828262
5	.99850060000000D-08	4.55271333456039
7	.34916069980000D-10	5.75522243976593
9	.12558053968507D-12	6.69174134731293
11	.46002346192139D-15	7.45939731597900
13	.17070109959924D-17	8.11013638973236
15	.63950679443501D-20	8.67504954338074
17	.24135523900157D-22	9.17424380779266
19	.91624945379266D-25	9.62148189544678
21	.34949616713818D-27	10.02660155296326
23	.13384127706799D-29	10.39688229560852
25	.51426503295719D-32	10.73786139488220
27	.19816290225791D-34	11.05384945869446
29	.76547005322218D-37	11.34827256202698
31	.29632521019136D-39	11.62389278411865
33	.11492961426845D-41	11.88297390937805
35	.44650416912406D-44	12.12739467620850
37	.17372863881865D-46	12.35872745513916
39	.67686738111581D-49	12.57830619812012
41	.26403744180160D-51	12.78727173805237
43	.10311183031761D-53	12.98660278320312
45	.40307905832263D-56	13.17715167999268
47	.15771528564250D-58	13.35965991020203
49	.61762758120557D-61	13.53477954864502
51	.24205844249103D-63	13.70308876037598
53	.94935572966301D-66	13.86509656906128
55	.37258913849320D-68	14.02125954627991
57	.14631994632779D-70	14.17198419570923
59	.57495083688707D-73	14.31763768196106
61	.22604516051140D-75	14.45855140686035
63	.88916445528822D-78	14.59502220153809
65	.34992725517642D-80	14.72732543945312
67	.13777482613197D-82	14.85570549964905
69	.54268409462464D-85	14.98039007186890
71	.21384498945674D-87	15.10158658027649
73	.84297815085328D-90	15.21948456764221
75	.33242222854855D-92	15.33425807952881
77	.13113306646420D-94	15.44607043266296
79	.51745826971555D-97	15.55506944656372
81	.20425489997170D-99	15.66139340400696
83	.80648677850522-102	15.76517224311829
85	.31852510414182-104	15.86652278900146
87	.12583636553611-106	15.96555709838867
89	.49725546383535-109	16.06238007545471
91	.19654364737682-111	16.15708589553833
93	.77703390980556-114	16.24976754188538
95	.30726860872517-116	16.34050846099854
97	.12153173210605-118	16.42938852310181
99	.48078477162854-121	16.51648402214050
101	.19023819356842-123	16.60186290740967
103	.75288283265538-126	16.68559312820435
105	.29801396254758-128	16.76773667335510

TABLE VII-3 (Contd.)

107	.117983807447733-130	16.84835433959961
109	.467177568831833-133	16.92749857902527
111	.185017449933365-135	17.00522422790527
113	.732844826027225-138	17.08158135414124
115	.290320438568824-140	17.15661764144897
117	.115028959481997-142	17.23037600517273
119	.455825507533317-145	17.30290293693542
121	.180654953265660-147	17.37423419952393
123	.716075809390663-150	17.44441390037537
125	.283873051363317-152	17.51347422599792
127	.112549509407738-154	17.58145213127136

TABLE VII-4

E_b/N_o = 12.31 dB

N	Pe	dB Improvement
1	.10000000000000D-03	.00000000000000
3	.29998000000000D-07	2.90569335222244
5	.99985000600000D-11	4.61263835430145
7	.34991600699980D-14	5.82829236984253
9	.12595800539969D-17	6.77400887012482
11	.46180203464692D-21	7.54851698875427
13	.17150993001760D-24	8.20458769798279
15	.64309970809162D-28	8.77378463745117
17	.24292502368179D-31	9.27650749683380
19	.92302445707432D-35	9.72670972347260
21	.35239281127015D-38	10.13435840606689
23	.13507057580298D-41	10.50682663917542
25	.51945083536422D-45	10.84971666336060
27	.20033976281067D-48	11.16739392280579
29	.77457026379102D-52	11.46332025527954
31	.30011618334906D-55	11.74028873443604
33	.11650411930789D-58	12.00058579444885
35	.45302653292289D-62	12.24610924720764
37	.17642436150973D-65	12.47844815254211
39	.68798653208314D-69	12.69894957542419
41	.26861561222443D-72	12.90876269340515
43	.10499382586044D-75	13.10887813568115
45	.41080446988125D-79	13.30015182495117
47	.16088238116992D-82	13.48333477973938
49	.63059606237333D-86	13.65908384323120
51	.24736301773184D-89	13.82798075675964
53	.97103202849533D-93	13.99053931236267
55	.38143881462615D-96	14.14721846580505
57	.14992995332036D-99	14.29843068122864
59	.58966563745569-103	14.44454312324524
61	.23203880114567-106	14.58588957786560
63	.91356158730300-110	14.72277164459229
65	.35985197340082-113	14.85546350479126
67	.14180985448498-116	14.98421311378479
69	.55908017285100-120	15.10924935340881
71	.22050404869108-123	15.23077845573425
73	.87001017108231-127	15.34899592399597
75	.34339077138002-130	15.46407341957092
77	.13558178809129-133	15.57617664337158
79	.53549457347657-137	15.68545341491699
81	.21156452675221-140	15.79204440116882
83	.83610007999140-144	15.89607715606689
85	.33051817424397-147	15.99767327308655
87	.13069185707355-150	16.09694361686707
89	.51690725537969-154	16.19399189949036
91	.20449504667696-157	16.28891587257385
93	.80919741375843-161	16.38180732727051
95	.32027530612367-164	16.47275090217590
97	.12679020636752-167	16.56182527542114
99	.50203904768033-171	16.64910793304443
101	.19882696880786-174	16.73466920852661
103	.78758197522510-178	16.81857466697693
105	.31202959836925-181	16.90088868141174

TABLE VII-4 (Contd.)

107	.123643816B7967-184	16.98166847229004
109	.49003015263932-188	17.06097245216370
111	.19424253934642-191	17.13885307312012
113	.77007766082621-195	17.21535921096802
115	.30534510440939-198	17.29053974151611
117	.12109087015909-201	17.36443877220154
119	.48027911183809-205	17.43710041046143
121	.19051791550459-208	17.50856637954712
123	.75585036892927-212	17.57887244224548
125	.29991064340948-215	17.64805793762207
127	.11901513962299-218	17.71615743637085

TABLE VII-5

E_b/N_0 = 13.35 dB

N	Pe	dB Improvement
1	.10000000000000D-04	.00000000000000
3	.29999800000000D-09	2.92815476655960
5	.99998500006000D-14	4.64685440063477
7	.34999160007000D-18	5.86991488933563
9	.12599580005400D-22	6.82079136371613
11	.46198020034650D-27	7.59913206100464
13	.17159099120020D-31	8.25817823410034
15	.64345996108106D-36	8.82976174354553
17	.24308249735691D-40	9.33444738388062
19	.92370442077128D-45	9.78629589080811
21	.35268366904300D-49	10.19534826278687
23	.13519407184539D-53	10.56902885437012
25	.51997205677448D-58	10.91297984123230
27	.20055866396493D-62	11.23159170150757
29	.77548581035478D-67	11.52834892272949
31	.30049776860093D-71	11.80606126785278
33	.11666268056128D-75	12.06703066825867
35	.45368369183262D-80	12.31316447257996
37	.17669610124572D-84	12.54606008529663
39	.68910793652588D-89	12.76706933975220
41	.26907756272779D-93	12.97735095024109
43	.10518381773887D-97	13.17789673805237
45	.41158475104603-102	13.36957216262817
47	.16120242082631-106	13.55312705039978
49	.63190718994804-111	13.72922301292419
51	.24789957948349-115	13.89844298362732
53	.97322567951392-120	14.06130433082581
55	.38233484583981-124	14.21826958656311
57	.15029564677935-128	14.36974883079529
59	.59115697841673-133	14.51611399650574
61	.23264655357874-137	14.65769886970520
63	.91603666160787-142	14.79480743408203
65	.36085932510340-146	14.92771267890930
67	.14221960830902-150	15.05666613578796
69	.56074599986054-155	15.18189549446106
71	.22118093587912-159	15.30360937118530
73	.87275930198769-164	15.42200088500977
75	.34450681033145-168	15.53724527359009
77	.13603466392499-172	15.64950823783875
79	.53733155568750-177	15.75893878936768
81	.21230937208605-181	15.86567521095276
83	.83911913626251-186	15.96984982490540
85	.33174146086059-190	16.07157945632935
87	.13118735805153-194	16.17097854614258
89	.51891369878434-199	16.26815199851990
91	.20530728180324-203	16.36319637298584
93	.81248452941283-208	16.45620226860046
95	.32160524620947-212	16.54725551605225
97	.12732815175466-216	16.63643836975098
99	.50421444270840-221	16.72382473945618
101	.19970646996479-225	16.80948495864868
103	.79113695607635-230	16.89348697662354
105	.31346622745178-234	16.97589397430420

TABLE VII-5 (Contd.)

107	.12422426353461-238	17.05676436424255
109	.49237488759099-243	17.13615536689758
111	.19518952260329-247	17.21411943435669
113	.77390160082270-252	17.29070782661438
115	.30688894699288-256	17.36596703529358
117	.12171406081682-260	17.43994474411011
119	.48279428255393-265	17.51268148422241
121	.19153286661271-269	17.58421897888184
123	.75994539124407-274	17.65459656715393
125	.30156261676784-278	17.72385001182556
127	.11967897510415-282	17.79201626777649

FIGURE VII-2

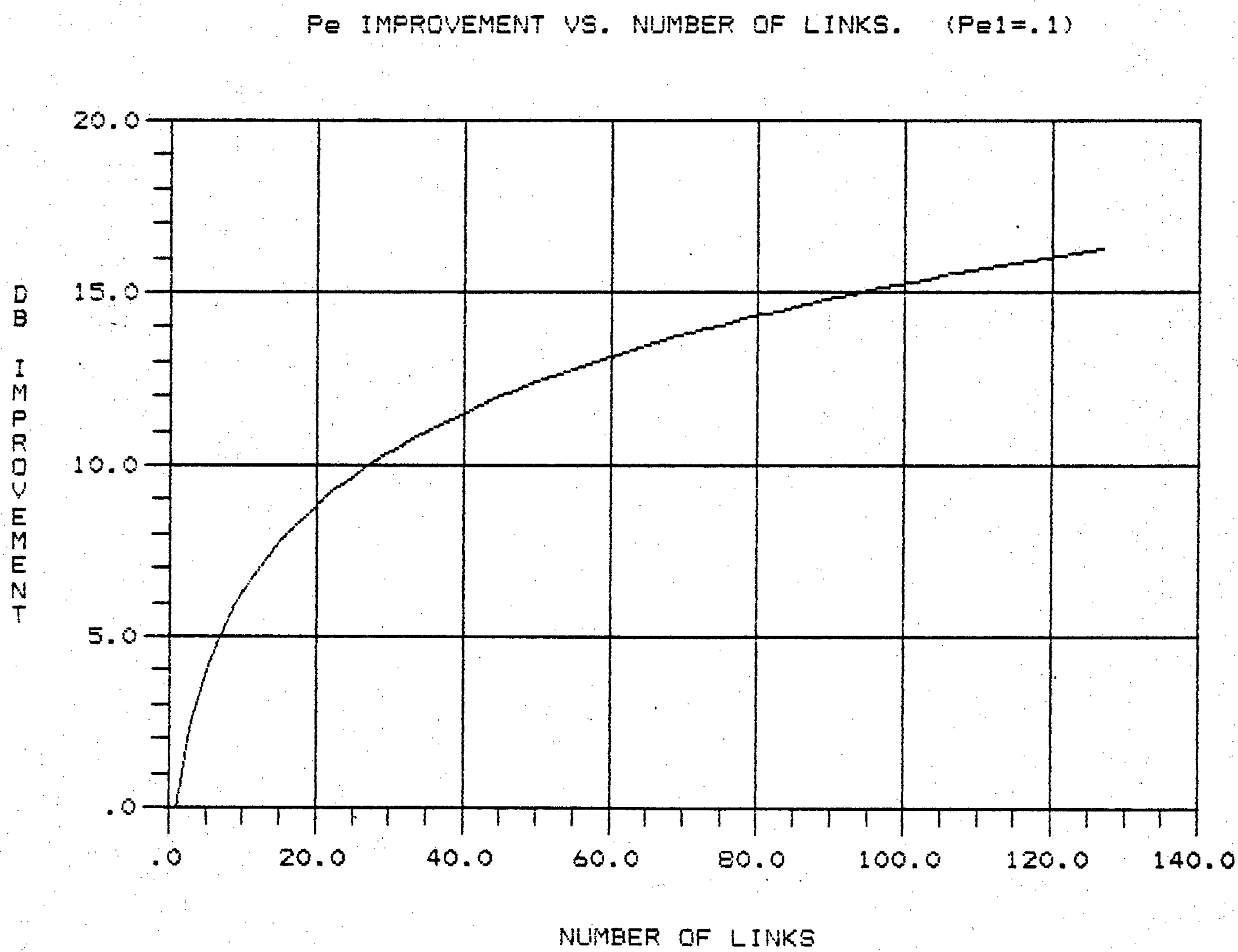

Pe IMPROVEMENT VS. NUMBER OF LINKS. (Pe1=.1)
20.0
15.0
10.0
5.0
.0
DB IMPROVEMENT
.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
NUMBER OF LINKS

FIGURE VII-3

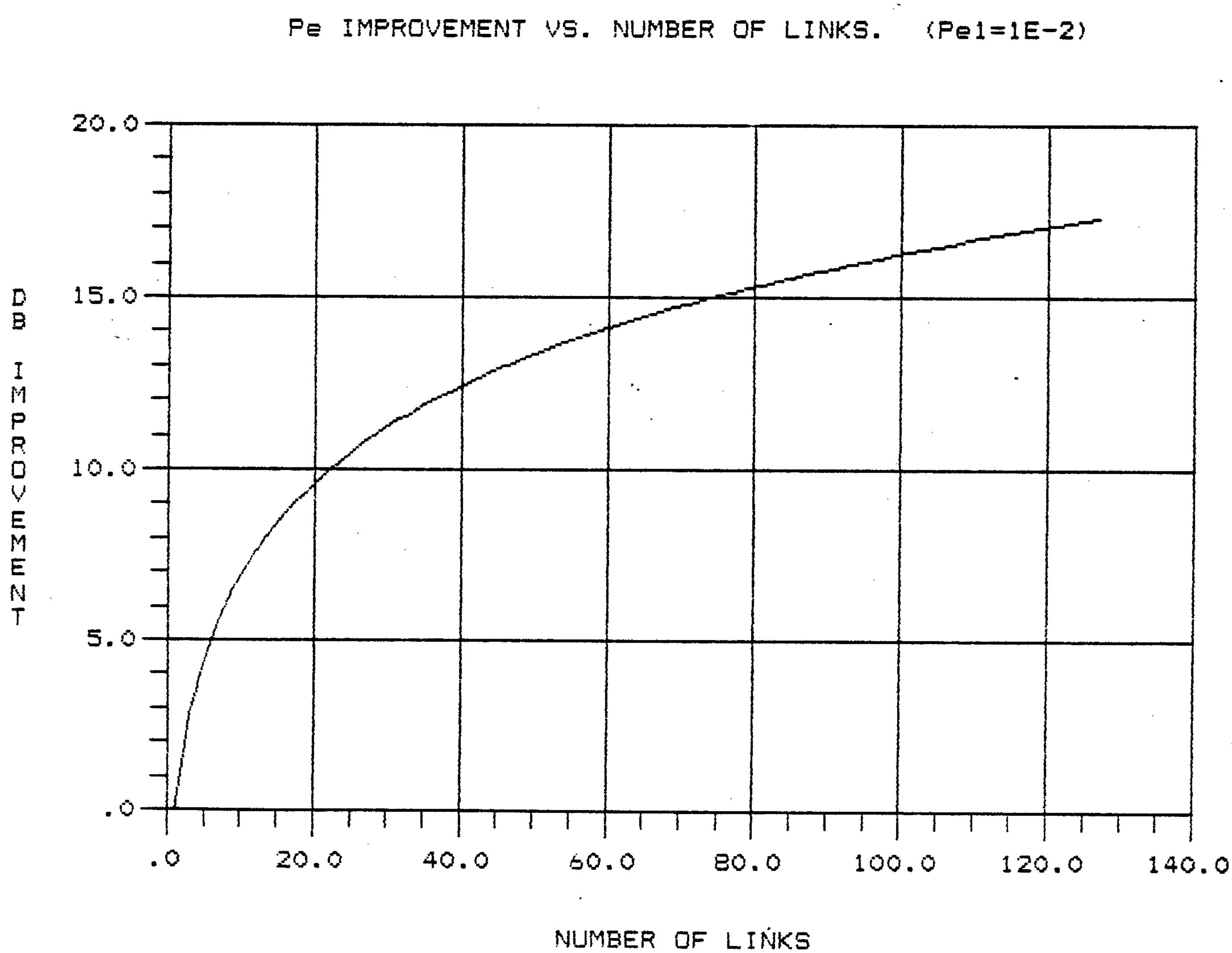

Pe IMPROVEMENT VS. NUMBER OF LINKS. (Pe1=1E-2)
20.0
15.0
10.0
5.0
.0
DB IMPROVEMENT
.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
NUMBER OF LINKS

FIGURE VII-4

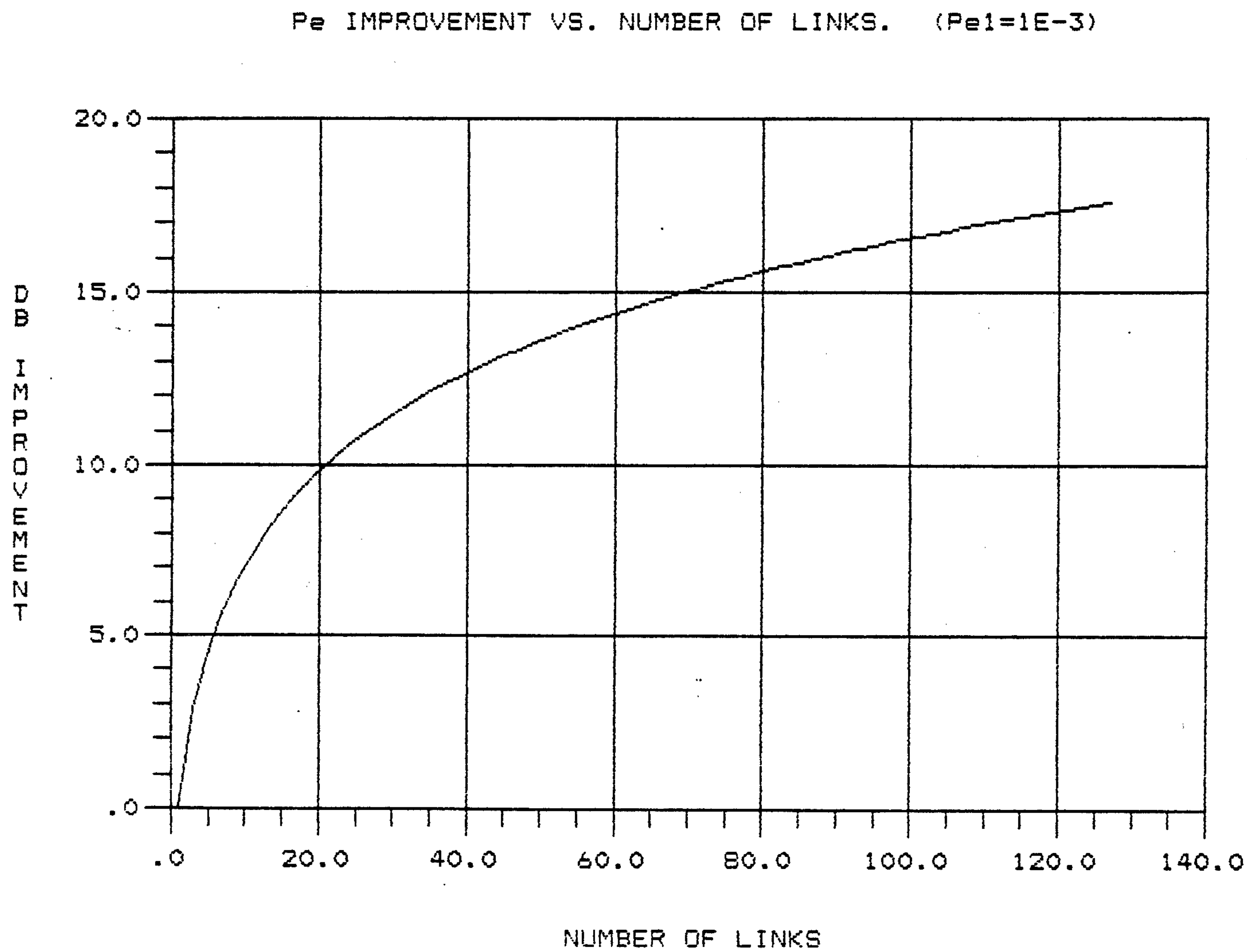
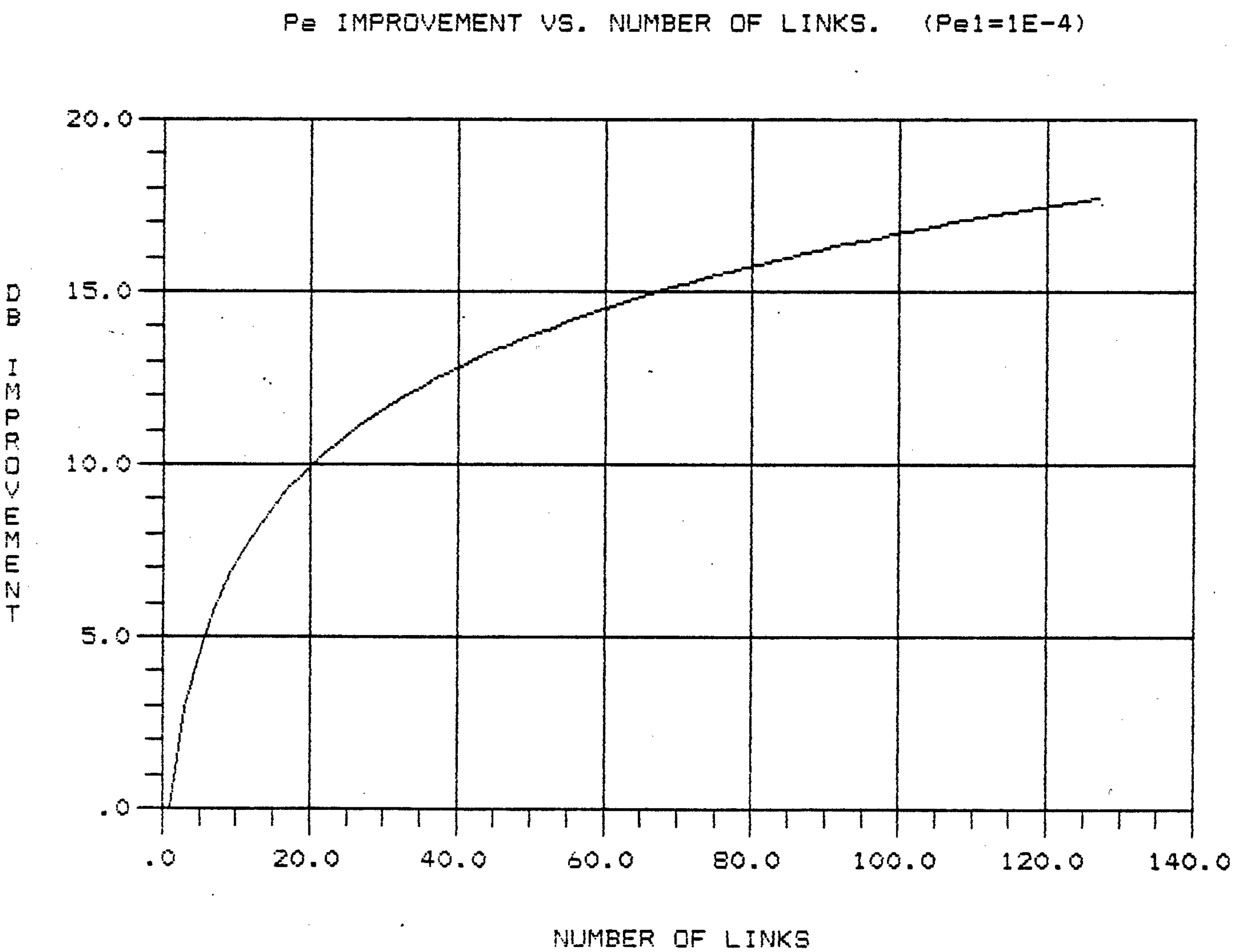

Pe IMPROVEMENT VS. NUMBER OF LINKS. (Pe1=1E-3)
DB IMPROVEMENT
20.0
15.0
10.0
5.0
.0
.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
NUMBER OF LINKS

FIGURE VII-5



Pe IMPROVEMENT VS. NUMBER OF LINKS. (Pe1=1E-4)
20.0
15.0
10.0
5.0
.0
DB IMPROVEMENT
.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
NUMBER OF LINKS

FIGURE VII-6

Pe IMPROVEMENT VS. NUMBER OF LINKS. (Pe1=1E-5)

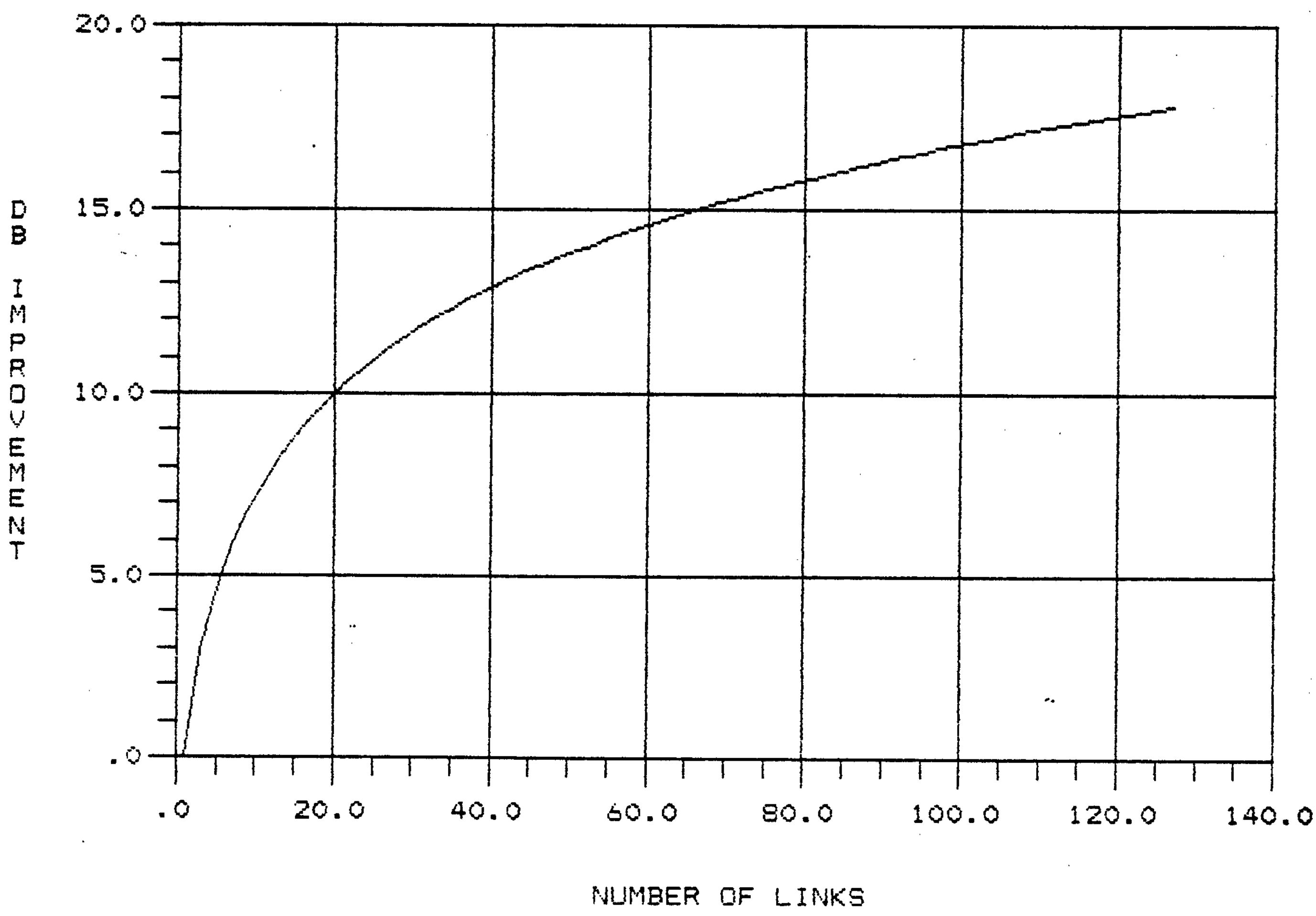
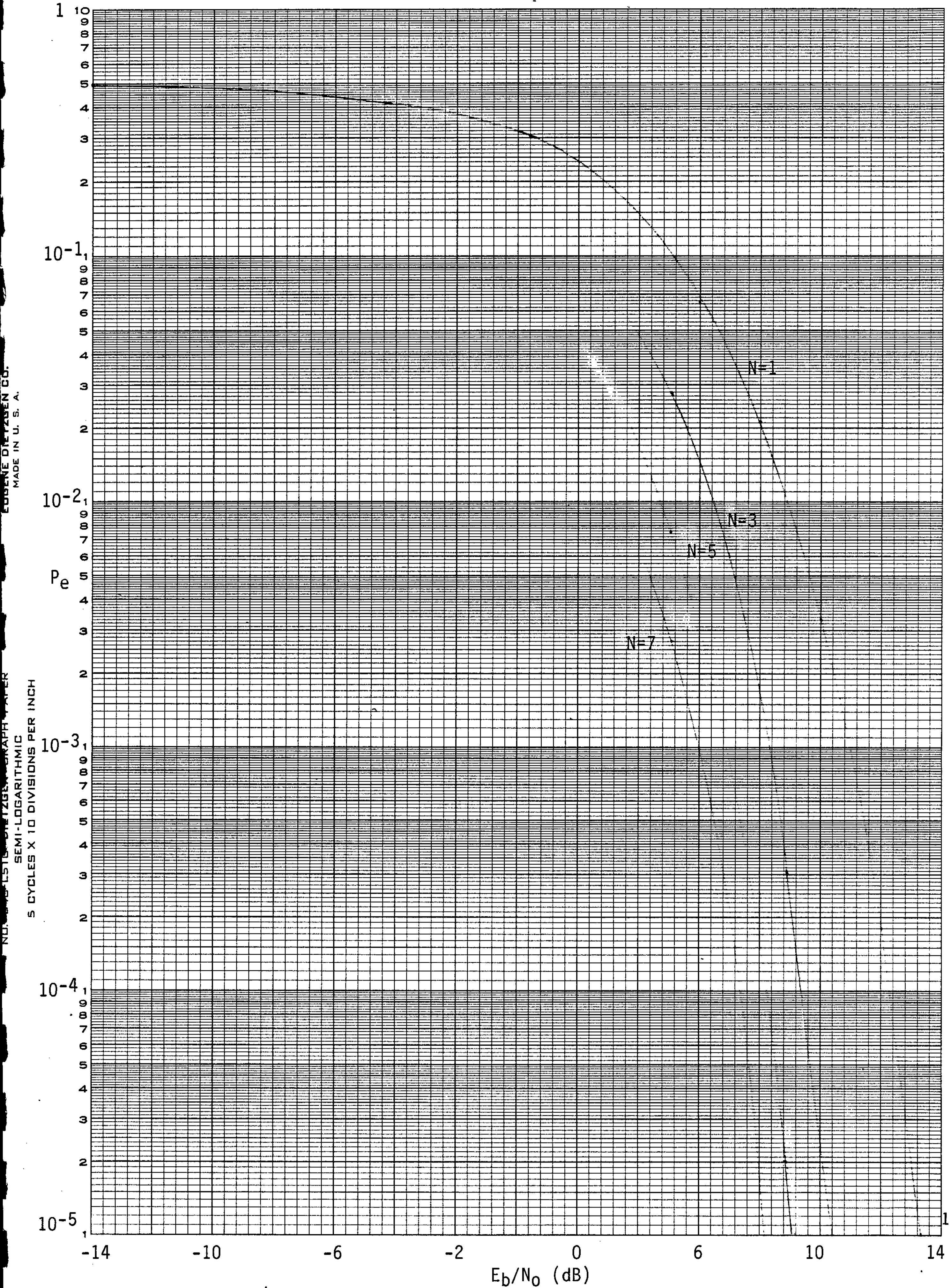
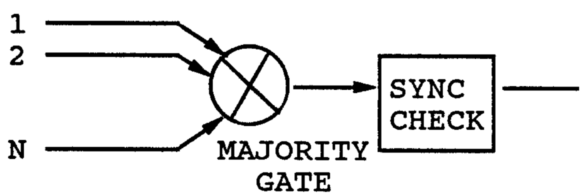


FIGURE VII-7



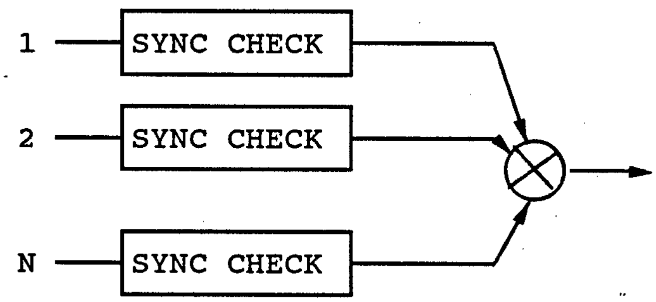
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
P_e
N=1
N=3
N=5
N=7
-14
-10
-6
-2
0
6
10
14
E_b/N_o (dB)
EUGENE DIETZGEN CO.
MADE IN U. S. A.
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

Now, if we use the full 50 distributed synchronization bits available in any packet (Section IV) and establish processing rules, an analysis of bit error rates (BERs) and link margin gains (+dB) can be determined. Two separate decision rules are depicted in Figures VII-8a and VII-8b.



VII-8a Method 1

Majority Logic on N links Then Sync Checked



VII-8b Method 2

N Links Each Sync Checked Then Use Majority Logic on "Good" Links

The task at hand is really twofold: 1) maintain link connectivity, and 2) maintain a sufficient level of link quality. If we concentrate on two potent comm-link threats, active jamming and nuclear event interference to propagation, in a parallel-link architecture with angular robustness, we would expect the following:

1) Any single jammer in a dynamic space-borne environment to possibly disrupt one of the links; and

2) Any nuclear event to be localized so as to disrupt a region no larger than a hemisphere, and more probably a half-hemisphere, angularly from any mode.

For Method 1, a jammer of a single link where $N \geq 3$ would expect little problem with connectivity but BER would suffer some, whereas for Method 2 the connectivity probability should be roughly the same (very slightly better) but the BER should be better since signals propagated through a very noisy channel would be eliminated earlier.

For Method 1, a nuclear event may disrupt several links and connectivity would have a higher probability of being lost, whereas for Method 2, if any one link maintains a sufficient signal-to-noise ratio, connectivity should be maintained.

In each of the cases, the numerical analysis bears out the arguments.

For both methods, assume that 50 of 50 synchronization bits must be correct for connectivity to be considered acceptable (though not analyzed here, less than 50 of 50 can be acceptable or be acceptable in certain instances).

Method 1

$$P \text{ (not connected)} = 1 - P \text{ (all L sync bits correct)}$$
$$= 1 - (1 - \tilde{P}_e)^L \simeq L\tilde{P}_e \text{ for } \tilde{P}_e << 1$$

where $\tilde{P}_e$ is the individual bit error probability induced by the majority logic decision. Note $\tilde{P}_e << P_e$.

Method 2

P (not connected) = P (all N links have at least one error in L sync bits)

$$= [1 - (1 - P_e)^L]^N \simeq (LP_e)^N \text{ for } P_e << 1$$

where P_e is the individual bit error probability. Note this expression assumes the N links are all statistically independent which is justified by the discussion at the beginning of this section.

Suppose now that $P_e = 10^{-5}$, N = 5, L = 50. Then for Method 2 we obtain,

$$P \text{ (not connected)} \simeq (50 \times 10^{-5})^5 = 3.125 \times 10^{-17}$$

For Method 1 we note that from Table VII-5 $\tilde{P}_e \simeq 10^{-14}$

so P (no connected) $\simeq 50 \times 10^{-14} = 5 \times 10^{-13}$.

In conclusion, decision rules corresponding to Method 2 are more favorable. Furthermore, since the numerical results show such a great advantage in both BER and link margin gains, a packet with 50 distributed synchronization pulses could support a robust architecture where no more than 5 to 9 (where the marginal improvement tends to fall off) parallel links need be used. Given that the final tradeoffs are not yet being made and that in some earlier cases we chose other than 5 to 9 parallel links, we

will proceed with the understanding that extra margin is built into some of the numbers. It is also noted that in the case of choosing 50 synchronization pulses in a 235-bit packet, no margin remained in the packet architecture. Also, some lower priority links can probably do without as much redundancy. Obviously, tradeoffs will continue, but for here the number of links listed in Section IV are, at least, a reasonable point of departure for continued tradeoff analyses...

VIII. COMSEC/TRANSEC, KEYING, AUTHENTICATION

COMSEC/TRANSEC, KEYING, AUTHENTICATION

COMSEC/TRANSEC

In the area of COMSEC/TRANSEC, the major hurdle for SDI will be in meeting Level 2 radiation requirements. The present equipment and architectures will support SDI needs in all other areas (assuming that no new encryption/decryption algorithms need to be developed), but device technologies in use at this time do not approach the required hardness levels. Indeed, the Level 1 requirements at this time are difficult to meet, but attainable.

The current state-of-the-art in COMSEC/TRANSEC includes digital encryptors ranging from one bit per second to hundreds of megabits per second, using any of several different algorithms and either of two modes of operation, with keying via resident variables or via remote electronic interface, and with the capability to change keys. One feature of these encryptors is their "fault intolerance"--i.e., their guarantee of shutdown in case of any internal failures that might compromise the security of the data.

One recent trend that seems likely to continue for SDI is the integration, or embedment, of COMSEC and TRANSEC functions directly into associated communications equipment instead of the use of separate COMSEC or TRANSEC boxes. VLSI efforts have reduced the COMSEC or TRANSEC function to a few integrated circuits, thus decreasing the size, weight, and power of the

overall function. As a result, the overhead penalties have increased in terms of mechanical packaging of a separate box and the risks involved for the embedder have decreased to the point that it makes more sense to include the COMSEC/TRANSEC function within other parts of the communications system.

The development of COMSEC/TRANSEC algorithms and their use in any particular application has in the past been determined by the government. Algorithms that have been used for space systems in the recent past include KG-28, KG-29, BAYLESS, KEESEE, and others, all of which entail serial digital data encryption and decryption. For SDI communication systems, any of these could potentially be used. Alternatively, the government might elect to develop entirely new algorithms for SDI, since it seems to be a "standalone" system that will not require interoperability with existing systems.

Three basic encryption operating modes have been considered for the communication system design. Each of these types of encryptors have applications in which they are best suited and those in which they are poorly suited. Table VIII-1 provides a direct comparison of these types. Encryptor Type 1 needs to be synchronized before data can be transmitted whereas Encryptor Type 2 does not require a specific synchronizing sequence. Operating data rates for Encryptor Type 1 or 2 are not an issue.

Encryptor Type 3, the block mode encryptor, is the most suitable for the SDI communication systems. The major drawback to this design is the timing of the block gate that must identify the first bit of encrypted data.

The code table required for the block encryptor can be generated by a variety of techniques, one of which is to operate Encryptor Type 1 in a burst mode by using the block gate to start and stop the clock to the encryptor shift register.

TABLE VIII-1 ENCRYPTOR COMPARISONS

ENCRYPTOR	DATA TYPE	BIT TIMES TO SYNCHRONIZE	ERROR MULTIPLICATION	IMMUNITY TO JAMMING	
				DURING SYNCHR	AFTER SYNCHR
1	CONTINUOUS	500 TO 1000	NO	POOR	GOOD
2	CONTINUOUS	NONE	YES	N/A	POOR
3	BURST	100	NO	GOOD	GOOD

KEYING

Depending upon the type of security device employed, a set of input variables (keys) are required. To maintain the determined security requirement any or all of the inputs will be treated as variables, whereas some may be fixed.

On board the satellites, keys for the security devices are derived from three sources: time of day, fixed parameters preset in PROMSs, and other variables communicated to the satellites (over-the-air parameters). Any or all of these sources can be employed for a given situation. Different layers of security can employ different sets and different mixtures of the same types of parameters.

1) <u>Time of Day</u> - It is assumed that time of day (TOD) information of sufficient accuracy is available on board the satellite and it will naturally be employed as part of the key of COMSEC and especially for TRANSEC. (Generally the TOD is augmented with a command sequence counter/authenticator and for purposes here this will all be considered as TOD.) Only one issue must be highlighted: The satellites are so far apart that time will appear to be different from satellite to satellite. Knowing ephemeris variables and managing the network to synchronize the arrival time of a signal with its

correspondingly correct COMSEC/TRANSEC keys will protect TOD as a useful (and preferred) piece of the key.

2) <u>Fixed Parameters</u> - A series of 100-200 unique codes can be pre-programmed prior to satellite launch and be managed by either a predetermined process or by signals from the ground. Such a configuration and management scheme is within current capabilities. The notion of visiting or refurbishing a satellite to change a PROM or re-initialize a tape is considered not feasible for SDI. If security tradeoff analyses eliminate consideration of over-the-air parameters, a scheme of fixed parameters (coupled with the TOD) should be employed.

3) <u>Over-the-Air Rekeying</u> (OTAR) - OTAR has one tremendously advantageous characteristic: immense flexibility--keys can be changed whenever the network manager chooses and any code can be used. It also has one major disadvantage: the fear that the OTAR link can be intercepted and exploited or be spoofed rendering the links useless. The state-of-the-art is such that OTAR information can be distributed/interlevered, coded, etc. to be accomplished with extremely low, acceptable risk.

Spoofing can be dealt with in an equally acceptable fashion.

<u>Conclusion</u> - TOD, presets, and OTAR can all be employed on SDI without significantly pushing the state-of-the-art for keying or key management. Some OTAR parameters will allow for more flexibility in growing and evolving the SDS as time goes on and would therefore be a very favorable technique. The probability of exploitation and spoofing can be made acceptable with design tradeoffs coupled to the actual security requirement. And, of course, different levels of security should be treated with separate analyses and the preferred mix of TOD, fixed, and OTAR parameters will most probably differ among the various security levels.

Current methods of keying encryption/decryption systems allow the addressing of individual satellites or ground stations as well as addressing of sub-nets or entire networks simultaneously. If a particular satellite is suspected of being compromised, it can be excluded from the ongoing communications through the use of a different key. Most newer systems allow rekeying, either from internally stored key variables or via encrypted variables sent over the link. The NSA has developed rekeying algorithms implementable in hardware for strategic systems that could also be applied to SDI COMSEC.

Most current cryptographic systems have resident processors to

ensure security and provide needed control sequences. These processors accept external control inputs and provide status outputs. In response to the control inputs, the processor conducts internal self-test, security checks, and alarm checks, as well as configuring the key generator for the selected mode of operation. Unique firmware-secured COMSEC/TRANSEC architectures can provide greater than 90% fault grade on internal nodes via system firmware. These processors help to meet the Security Fault Analysis (SFA) requirements of COMSEC equipment.

AUTHENTICATION

There are currently three authenticate methods that have been used in conjunction with the decrypt/command uplink. They are as follows:

1. KIR-23
2. KGR-29
3. KGX-60

The KIR-23, currently being upgraded on the KEYWAY program as the KIR-123, is block decryptor followed by an authenticator. The block decryptor, decrypts and gives the entire word to the authenticate logic. The word is made up of four segments: a command data portion, a fill bit, and actual authenticate word. The authenticate word, which is an internally stored count of valid authenticated commands, is incremented (+1) with every valid authenticate and can be reloaded with the command data filed. During normal operation the command data is only output if the authenticate was valid. The command rate is:

KIR-23	6 Commands Per Second
KIR-123 (KEYWAY)	280 Commands Per Second

The KGR-29 is a serial machine which passes variable length command data, although authenticate dictates a minimum and a maximum length. This authenticate algorithm, unlike the KIR-123,

passes "unauthenticated" data as well as authenticated data. The authenticate output is an "Accept" or "Reject" pulse at the end of the authenticate cycle. The authenticate cycle begins upon receipt of the correct coded data. The KGR-29 is a ternary data box with three valid decoded commands, as follows:

1. Authenticate
2. Fill
3. Increment

The serial bit stream is composed of two parts, the command data and the authenticate data. The first four bits on the authenticate are decoded to determine which command is present. The authenticate word contains three segments, the fixed data portion, the vehicle (V-word) word segment and the time word section (T-word). The V word is incremented (+1) for each valid authenticate. Both T and V words can be altered by use of the fill or increment commands. The increment commands will add one to the T-word and set the V-word to 1. The fill command puts the immediately following command data bits into the T-word and again sets the V-word to 1. Neither command will be executed unless the command was authenticated. The KGR-29 can also be used to transmit serial data in a continuous manner when authentication is not necessary, such as a long data transfer. The maximum bit rate is 128 Kbps for this unit.

The third type of authentication that has been used is that used

in the KGX-60. The output of the KG (plain text) is in a quasi-telemetry format. A 24-bit sync word is used in order to synchronize the authenticate. After the sync word is detected three consecutive times in the serial bit stream from the KG (KG-29/59), the authenticate proceeds. Until sync is found all data is passed unmodified through the unit. After sync, the 4 bytes of command data are temporarily stored and replaced with previously authenticated data. The assembled command data is exclusively "OR"ed with on-board IRIG "B" time and checked for correctness using a BCH error-checking algorithm. When the BCH checks okay, authenticate, the entire command block, command data plus BCH extension is transmitted during the next format. When the authenticate is not valid the command data block is inhibited and zeros are transmitted followed by the actual BCH remainder. The current bit rates for the KGX-60 is 96K BPS or 196K BPS.

Each of the three methods of authentication has a specific use. The KIR-23 method works well for low data rates when only command data is required and security is paramount, since the KIR-23 does not output unless authentication is valid. Increasing the command rate to above 1,000 command per second would be easily obtainable using current technology. The KG-29/KG-57 family is useful for transmitting long data streams, such as those used in reloading or updating memory banks. This system is not as secure, however, since it depends on the processor to act on the accept-reject pulse after receipt of the actual command data. The KGX-60 method has the advantage of passing either

authenticated data or ordinary traffic, that does not require authentication.

Additional security can be added to any of the above systems by adding security checks within the receiving processor. The KGX-60 function, for instance, uses a Row-Column check on several commands for further verification.

In essence, the optimum method of authentication depends on the data rate as well as the overall system capabilities.

SUMMARY

Barring any new special security requirements, the technology for COMSEC/TRANSEC, KEYING (to include key management), and AUTHENTICATION now exists and is available for SDI/SDS. The specific design needs to be determined using the channel requirements which must be validated for the entire system.

IX. SIZE, WEIGHT, AND POWER

SIZE, WEIGHT, AND POWER

EHF and laser communication terminal size, weight, and power estimates have been generated for each of the spaceborne SDS elements. The results for EHF technology is presented in Tables IX-4 through IX-8 while the lasercom results are discussed at the end of this section. The EHF technology will be discussed first.

EHF Estimates

EHF terminal estimates are based on the use of monolithic phased arrays, as described in Section V. This technology utilizes solid state power amplifiers embedded in the transmitters' arrays. It is expected that this technology will be available within five to ten years or perhaps sooner if sufficient research funds are directed to this effort.

The receiver and transmitter electronics assume use of current LSI technology and are based on systems of like complexity currently being produced. Each communication system's size, weight, and power estimate incorporates allowances for the use of error correction, interleaving, spread spectrum, and encryption.

Tables IX-1 through IX-3 provide the basis for the estimates of each of the SDS elements shown in Tables IX-4 through IX-8. Payload estimates have been separated from antenna estimates since the antenna structure would be external or near conformed to the spacecraft.

TABLE IX-1
<u>60 GHZ</u>

<u>Transmitter Exciter</u>

Size	186 Cubic Inches
Weight	14.7 Pounds
Input Power	26 Watts

<u>Transmit Antenna & Power Amplifier (100W)</u>

Size	216 Cubic Inches
Weight	6 Pounds
Input Power	667 Watts
Efficiency	15%

<u>Receiver</u>

Size	186 Cubic Inches
Weight	14.7 Pounds
Input Power	26 Watts

<u>Receiver Antenna</u>

Size	216 Cubic Inches
Weight	5 Pounds

TABLE IX-2
44 GHZ

Transmitter Exciter

Size	186 Cubic Inches
Weight	14.7 Pounds
Input Power	26 Watts

Transmit Antenna & Power Amplifier (100W)

Size	402 Cubic Inches
Weight	11 Pounds
Input Power	500 Watts
Efficiency	20%

Receiver

Size	186 Cubic Inches
Weight	14.7 Pounds
Input Power	26 Watts

Receiver Antenna

Size	402 Cubic Inches
Weight	10 Pounds

TABLE IX-3
20 GHZ

Transmitter Exciter

Size	186 Cubic Inches
Weight	14.7 Pounds
Input Power	26 Watts

Transmit Antenna & Power Amplifier (100W)

Size	1944 Cubic Inches
Weight	46 Pounds
Input Power	400 Watts
Efficiency	25%

Receiver

Size	186 Cubic Inches
Weight	14.7 Pounds
Input Power	26 Watts

Receiver Antenna

Size	1944 Cubic Inches
Weight	45 Pounds

BSTS

The BSTS estimate is based on the use of three 60 GHz transmit/receive units so that each of the 60 GHz links can operate concurrently. The BSTS-to-BSTS links utilize two transmit as well as two receive arrays to obtain the required angular coverage. The remaining 60 GHz links (to the SSTSs and CV/SBIs) only require one of these units. The 44 GHz and 20 GHz payloads are receive-only and transmit-only, respectively, with angular requirements such that each system requires only one antenna array.

TABLE IX-4
BSTS

60 GHz Communication Package	
Payload (3 Tx/Rx Units)	
Size	1116 Cubic Inches
Weight	88.2 Pounds
Power	156 Watts
Transmit Antennas & Power Amplifiers (4 Units)	
Size	864 Cubic Inches
Weight	24 Pounds
Power	2000 Watts
Receiver Antennas (4 Units)	
Size	864 Cubic Inches
Weight	20 Pounds
44 GHz Communication Package	
Payload (1 Rx)	
Size	186 Cubic Inches
Weight	14.7 Pounds
Power	26 Watts
Receiver Antenna (1 Unit)	
Size	402 Cubic Inches
Weight	10 Pounds

TABLE IX-4 (Contd.)

20 GHz Communication Package

Payload (1 Tx)	
Size	186 Cubic Inches
Weight	14.7 Pounds
Power	26 Watts
Transmit Antenna & Power Amplifier	
Size	1944 Cubic Inches
Weight	46 Pounds
Power	400 Watts
Power Converter	
Size	1771 Cubic Inches
Weight	125 Pounds
Efficiency	70%

Summary

Payload	
Size	3259 Cubic Inches
Weight	243 Pounds
Power	3726 Watts
Antennas	
Size	4074 Cubic Inches
Weight	100 Pounds
Power	2400 Watts

SSTS

The SSTS estimate is based on the use of three 60 GHz transmit/receive units to enable simultaneous operation of each 60 GHz link. The SSTS to SSTS and SSTS to CV/SBI links utilize two transmit and two receive arrays each to obtain the correct angular coverage. The SSTS to BSTS link requires only one array each for transmit and receive. The 44 GHz and 20 GHz payloads are receive and transmit only respectively and require only one array each of the appropriate type.

TABLE IX-5
SSTS

60 GHz Communications Package

Payload (3 Tx/Rx Units)	
Size	1116 Cubic Inches
Weight	88.2 Pounds
Power	156 Watts
Transmit Antennas & Power Amplifiers (5 Units)	
Size	1080 Cubic Inches
Weight	30 Pounds
Power	2000 Watts
Receiver Antennas (5 Units)	
Size	1080 Cubic Inches
Weight	25 Pounds

TABLE IX-5 (Contd.)

44 GHz Communication Package	
Payload (1 Rx)	
Size	186 Cubic Inches
Weight	14.7 Pounds
Power	26 Watts
Receiver Antenna (1 Unit)	
Size	402 Cubic Inches
Weight	10 Pounds
20 GHz Communication Package	
Payload (1 Tx)	
Size	186 Cubic Inches
Weight	14.7 Pounds
Power	26 Watts
Transmit Antenna & Power Amplifier (1 Unit)	
Size	1944 Cubic Inches
Weight	46 Pounds
Power	400 Watts
Power Converter	
Size	1771 Cubic Inches
Weight	125 Pounds
Efficiency	70%
Summary	
Payload	
Size	3259 Cubic Inches
Weight	243 Pounds
Power	3726 Watts
Antennas	
Size	4506 Cubic Inches
Weight	111 Pounds
Power	2400 Watts

CV/SBI

The CV/SBI estimate is based on the use of five 60 GHz transmit/receive units to accommodate the CV to BSTS, SSTS, CV, ERIS, and GSTS links. The CV to SSTS and CV to CV links require two transmit and two receive arrays each to obtain sufficient angular coverage. The remaining 60 GHz links can be accommodated with a single array of each type.

TABLE IX-6
SBI-CV

60 GHz Communication Package		
Payload (5 Tx/Rx Units)		
	Size	1860 Cubic Inches
	Weight	147 Pounds
	Power	260 Watts
Transmit Antennas & Power Amplifiers (7 Units)		
	Size	1512 Cubic Inches
	Weight	42 Pounds
	Power	2668 Watts
Receiver Antennas (7 Units)		
	Size	1512 Cubic Inches
	Weight	35 Pounds
Power Converter		
	Size	1943 Cubic Inches
	Weight	137 Pounds
	Efficiency	70%
Summary		
Payload		
	Size	3803 Cubic Inches
	Weight	284 Pounds
	Power	4183 Watts
Antennas		
	Size	3024 Cubic Inches
	Weight	77 Pounds
	Power	2668 Watts

GSTS

The GSTS estimate is based on one 60 GHz transmit/receive unit to accommodate the link to the CV/SBI as well as a single 20 GHz transmitter to communicate to the GEP. It is expected that the angular coverage can be met with single transmit and receive arrays.

TABLE IX-7
GSTS

60 GHz Communication Package		
Payload (1 Tx/Rx Unit)		
	Size	372 Cubic Inches
	Weight	30 Pounds
	Power	52 Watts
Transmit Antenna & Power Amplifier (1 Unit)		
	Size	216 Cubic Inches
	Weight	6 Pounds
	Power	667 Watts
Receiver Antenna (1 Unit)		
	Size	216 Cubic Inches
	Weight	5 Pounds
20 GHz Communication Package		
Payload (1 Tx)		
	Size	186 Cubic Inches
	Weight	14.7 Pounds
	Power	26 Watts

TABLE IX-7 (Contd.)

Antenna & Power Amplifier (1 Unit)

Size	1944 Cubic Inches
Weight	46 Pounds
Power	400 Watts

Power Converter

Size	1227 Cubic Inches
Weight	87 Pounds
Efficiency	70%

Summary

Payload

Size	1785 Cubic Inches
Weight	132 Pounds
Power	1636 Watts

Antennas

Size	2376 Cubic Inches
Weight	57 Pounds
Power	1067 Watts

ERIS

The ERIS estimate is based on one 60 GHz transmit/receive unit to accommodate the link to the CV/SBI as well as a single 44 GHz receiver to communicate with the ERIS farm battle manager. It is estimated that two transmit and receive arrays will be required at 60 GHz to provide the needed angular coverage. At 44 GHz a single array will suffice.

TABLE IX-8
ERIS

60 Ghz Communication Package	
Payload (1 Tx/Rx Unit)	
Size	372 Cubic Inches
Weight	30 Pounds
Power	52 Watts
Transmit Antenna (2 Units)	
Size	432 Cubic Inches
Weight	12 Pounds
Power	667 Watts
Receiver Antenna (2 Units)	
Size	432 Cubic Inches
Weight	10 Pounds
44 GHz Communication Package	
Payload (1 Tx)	
Size	186 Cubic Inches
Weight	14.7 Pounds
Power	26 Watts
Receive Antenna (1 Unit)	
Size	402 Cubic Inches
Weight	10 Pounds
Power Converter	
Size	750 Cubic Inches
Weight	53 Pounds
Efficiency	70%
Summary	
Payload	
Size	1308 Cubic Inches
Weight	98 Pounds
Power	1064 Watts
Antennas	
Size	1266 Cubic Inches
Weight	32 Pounds
Power	667 Watts
LASERCOM	

LASERCOM

Due to an insufficient applicable analytical baseline, size, weight and power projections for free-space SDS communications applications cannot be included with confidence in this report.

Few lasercom studies and developments have aimed at operational uses, and these have been for quite unique single-string applications. Alternatively, highly publicized lasercom experiments have focused primarily on feasibility demonstrations. These did not incorporate sufficiently robust design philosophies to permit direct extension to an operational SDS environment. Hardware designs have in all cases, however, been constrained significantly, either by the need to displace existing alternative capabilities or by size/weight/power budgets dictated by a potential host vehicle or program sponsor. Of necessity, thus, wide confidence intervals in size, weight, and power trades have persisted. Alternatively, lasercom reliability/lifetime analyses have shown divergent results and conclusions when performed by independent and/or competing study teams.

For these reasons, we recommend that hardware definition studies be undertaken immediately to definitize and refine the currently disparate estimates of lasercom terminal impact on SDS host spacecraft. Such studies should be commissioned by the SDIO, funded through the spacecraft hardware prime contractors, and

should proceed in concert with the SDS architecture participants, from a common technical requirements baseline to generate a valid development planning perspective for lasercom hardware.

In any case, it is important to contrast the size, weight, and power projections developed in this section for EHF communications link hardware with the corresponding numbers profferred by laser systems contractors to which we have been afforded access. Whereas virtually no relevant productized lasercom size, weight, and power budgets are at hand, EHF budgets developed herein are based on experience with existing manufacturing-oriented hardware production programs.

X. EHF/LASER COMPARISON

EHF/LASER COMPARISON

Introduction

Inspection of technical and popular literature sources shows a burgeoning number of research and application developments in EHF and lightwave communications. Such readily available sources, however, do not usually address those current military developments which are most relevant to free-space communications applications. For the most part, industrial and fiber optic laser applications as well as short-range, transmit-power-intensive EHF applications are spotlighted. This report, however, considers existing results and projected capabilities of EHF and free-space laser communications systems applications including fiber-optic communications (FOC) and reported military developments.

The foremost application driving low power laser system development is now commercial FOC. Close behind are all-solid-state reprographics uses (printing, copying, scanning, facsimile transmission, etc.). The military use of low power laser systems has already begun, since this technology offers promising advantages. Ground-based FOC systems are inherently EMP-hard and require no emanations shielding (TEMPEST) while offering large weight and power advantages over wire and cable-based alternatives. Ultra-wideband signaling (2-20 gigabits per second [GBPS]) is today being demonstrated in the laboratory with solid-state lasers. Solid-state copy and facsimile machines are

expected to be available within 5 years. These should be more reliable than today's electrostatic machines and will probably offer workers a "single-station office" with computer interface, printing and high quality graphics--nearly comparable to that of photographic images (1500-3000 dots per inch).

Of all laser types investigated to date, only those based on III-V materials [combinations of one or more of gallium (Ga), Aluminum (Al),and Indium (In) with arsenic (As) and/or phosphorus (P)] satisfy commercial FOC and reprographics requirements.

Space Communications

Free-space laser communications investigations began almost simultaneously with the discovery of the He-Ne laser in the early 1960s. These have continued at steady but subdued interest levels for applications ever since. Although He-Ne is no longer a serious contender for communications, investigations into the potential of gaseous CO_2, solid-state neodymium-doped, alexandrite and III-V material diode lasers have continued. Since facilities for such work require the investment of considerable capital and research, it is not surprising that work on each type of laser (and its unique frequency) has been undertaken primarily by a single organization. For example, infrared CO_2 laser communications, originally pursued by Hughes Aircraft Co., now appears of interest only to the European Space Agency (ESA).

Neodymium-doped substances (such as yttrium-aluminum-garnet [Nd^+:YAG], yttrium-aluminum oxide [Nd^+:YAlO] and various glasses [Nd^+:glass] appear to be the province of McDonnell-Douglas Astronautics Company (MDAC). Alexandrite is championed by Allied-Signal Corporation. However, III-V materials are, as previously noted, the most widely investigated and used at present. In the United States RCA, TRW, and ATT are highly visible, while Hitachi, Nippon Telephone and Telegraph and Thomson-CSF are prominent overseas in high data rate (hundreds of MBPS) FOC applications. Until this time, however, the established, evolving history of RF space communications, along with the technical difficulties inherent in space-ground transmission through the atmosphere, has effectively limited consideration of free-space laser communications only to those potential applications which may not be able to sustain an RF alternative.

Those free-space applications suited to lasers are largely also suited to EHF/millimeter-wave signaling. The product state-of-the-art at EHF reflects a history of sustained research, development and product funding. Significant United States government involvement in support of C^3/EW projects is quite apparent, along with corollary developments in Europe and Japan. Military or quasi-military programs have often paved the way for commercial satellite and space station exploitation, and millimeter-wave frequencies are no exception. A great deal of "applications-pull" investment is now reflected in the strong

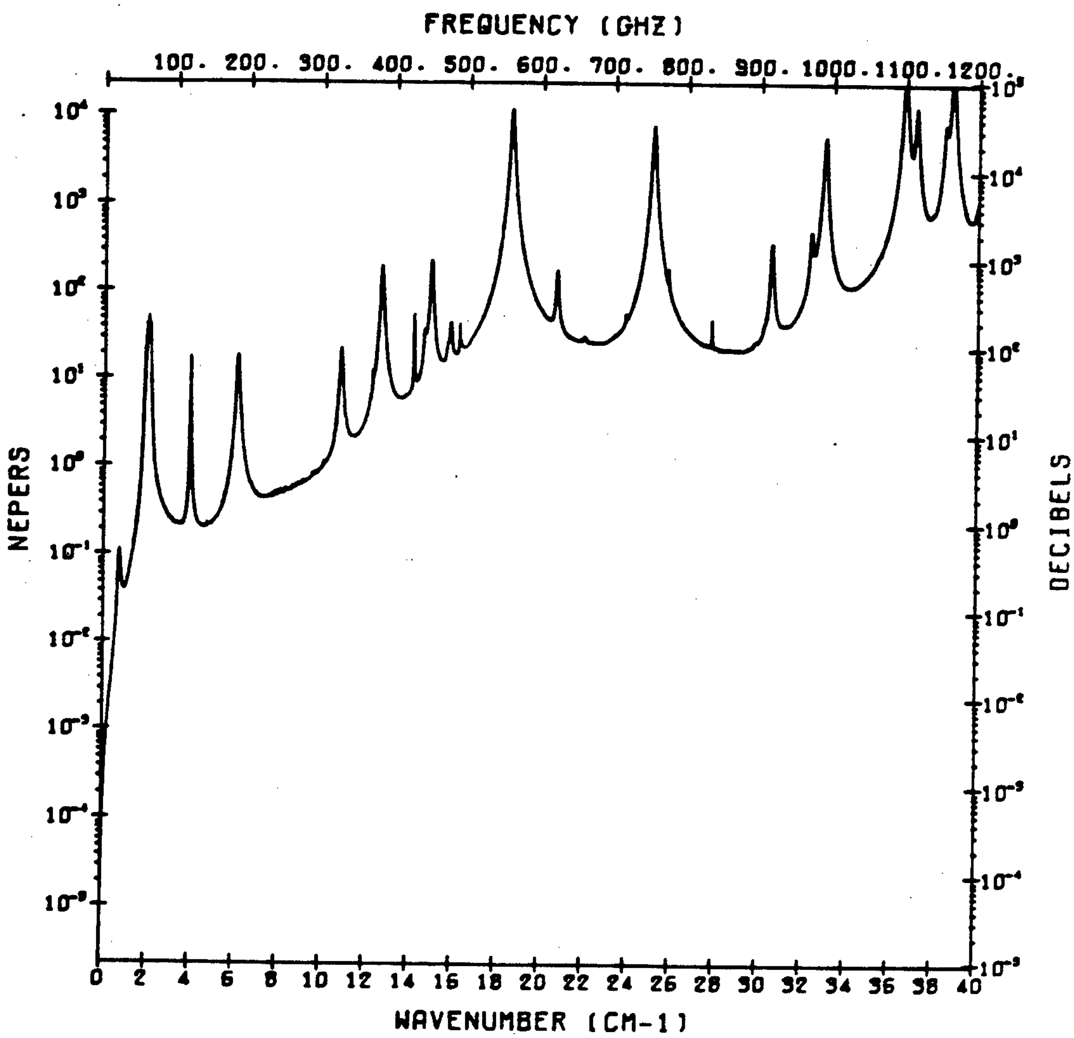
competitive position of several firms in the EHF communications marketplace.

Phenomenology

Alternating regimes of semi-transparency and opacity characterize the EHF/millimeter-wave band. "Windows" (Figure X-1) at 30-55 GHz, 62-115 GHz, 125-175 GHz, and 190-300 GHz become progressively less transparent due to even denser absorption features at frequencies beyond 300 GHz. Between these window regions there exist radio opaque absorption "curtains" due to O_2 and H_2O centered at 60, 118, and 180 GHz. At these latter frequencies, RF energy cannot readily penetrate the earth's atmosphere. These "curtain frequencies" are thus appropriate for exoatmospheric communications (space crosslinks), while the "windows" are best suited for space-to-ground up/down links.

For technological reasons, the EHF band has been utilized most heavily near its low frequency end with progressively less use evident in the upper regions. Certain tactical ground and airborne radars, along with the FLAGE/LEDI missile, operate at frequencies near 35 GHz. A commercially successful European marine/harbor radar system operates between 36 and 40 GHz. EHF space communications developments have proceeded chiefly at 30 GHz (ACTS) and 44 GHz (MILSTAR uplinks). LPI applications for space crosslinks, tactical communications and radar altimetry have been the focus of 60 GHz R&D thrusts. Radar and C^3

FIGURE X-1



Zenith Attenuation (Nepers, Decibels) Through the Entire Atmosphere (U.S. Standard)

requirements have again driven efforts in the 85-110 GHz frequency window. Very limited use of frequencies beyond 110 GHz is in evidence, although some R&D has been supported. (Some missile radar and fuze development efforts are underway at 140 GHz.) United States military technological thrusts are focused on: 1) developing reliable, solid-state EHF sources (fundamental and harmonic frequency Gunn diodes); 2) low noise receivers operating between 60-140 GHz; and 3) electronically agile solid-state antenna arrays (simplex, and, with more complexity, duplex) templated on the RADC 20 GHz effort which will be extensible throughout the band.

Current Technical Issues

General

There are significant technical communications issues which will require hardware demonstrations in the near term to increase confidence in SDI systems capabilities. These include: accurate, precise, low-jitter antenna positioning; transmission power sufficient to close all required links at system end-of-life (EOL); and, transient and total-dose nuclear hardening of associated components and subsystems. Derivative pointing and tracking requirements encompass rapid, accurate antenna/beam slewing over large solid angles in response to spacecraft dynamics and line-of-sight constraints. The achievement of electronically-agile antennas at the frequencies of interest is a

central technical concern. To maintain both jam-resistant links and the robust-geometry network presented in earlier sections, the ability of such antennas to direct a transmit or receive beam toward any one of a number of alternative internetted SDS platforms is a critical and essential requirement.

EHF/Millimeter Waves

At EHF, a predominant concern is the selection of one or more baseline communications frequencies appropriate to the range of SDI missions in the time frame of interest. Considerable experience has been gained with traveling-wave tube amplifier (TWTA) and IMPATT sources below 100 GHz. However, serious design manufacturing and reliability issues persist with TWTAs, and IMPATT diodes are inherently noisy devices. These concerns now appear to preclude consideration of tube sources above 50 GHz for space communications use. Nevertheless, significant progress has been demonstrated in the development of Gunn devices, and hybrid and space-fed power combining techniques now make solid-state sources competitive, up to 60 GHz. To satisfy robustness requirements for multiple, simultaneous links, employ high-gain, electronically-steered (vice mechanically repositioned) transmit and receive antenna arrays.

Ultimately an EHF space communications system for SDS would feature electronically-agile, beam-steered, transmit and receive antenna arrays. Building upon the successful RF electronics

development history at S, C, X, and K band, these agile arrays would embody: multiple-link availability/target tracking over large solid angles; system robustness through platform internetting; significant anti-jam capability, including steerable nulls; and, graceful performance degradation with the loss of individual module elements. Each individual array should be able to communicate with all other mission platforms in its field of view (between $\pm 45^{o}$ and $\pm 60^{o}$). SDS constellation geometry, not total numbers of platforms, would then dictate the number and placement of spare terminals for the SDS. Overall communications system size, weight, and power requirements would not necessarily increase on future spacecraft, as more SDS nodes are added to space segment constellations.

Laser

The proposed coherent near-IR SDI laser communications systems would required operation through a variety of disturbed, high-background environments and still demonstrate effective residual anti-jam capability. In addition to an approximate 10 dB signal-to-noise ratio improvement over equivalent direct detection schemes, coherent laser communications systems would only be threatened by on-axis jammers or by direct attack. With their extremely narrow effective beamdwidths, coherent laser systems would also permit continued link operations even when a receiver platform infrequently transits the solar disk. Our discussion here will focus on a coherent lasercom system as the preferred (more link margin, better AJ, and no sun problem compared to

noncoherent systems) long-term laser candidate for SDS. This assumption is consistent with the general consensus* of the community regarding laser communications.

It does not appear that current III-V materials technologies will be able to produce individual, long-life diode lasers with output power sufficient to close all required SDI links. Hybrid power combining techniques require mechanical positioning (or external cavity stability) to within 0.1 micrometers. Thus, although feasible for potential benign environment uses, mechanical power combining does not appear promising for space system applications. Monolithic power combining of several injection-locked diode lasers fabricated side-by-side on the same substrate, however, appear quite capable of ultimately satisfying power, beam quality and beam steering requirements. Nevertheless, the developmental history of such devices has consistently demonstrated the necessity of performing device design model (as well as acceptance, power output, stability and life) testing under conditions which simulate actual flight configuration as nearly as possible.

*See the following: 1) "Space Coherent Optical Communications System-An Introduction," by V.W.S. Chan, in the IEEE Journal of Lightwave Technology, April 1987; 2) "Coherent Optical Space Communications System Architecture and Technology Issues," by V.W.S. Chan in the Proceedings SPIE (San Diego), September 1981; 3) "Space Data Relay Networks," by F.W. Floyd, in the M.I.T. Lincoln Laboratory TR-572, December 3, 1981; 4) "Heterodyne and Coherent Optical Fiber Communications," by T. Okoshi, in the IEEE Transactions on Microwave Theory Technology, August 1982; and 5) "Laser Communications Experiment I, by T.R. Bristow and S.D. Simmons, in RADC-TR-86-156 (Vol. 1), November 1986.

A separate concern is the amplitude, frequency, and phase stability of diode lasers suitable for local oscillator applications. For coherent space communications precise frequency tunability will also be required to compensate for relative doppler shifts between platforms. Doppler frequency shifts induced by relative platform motion are likely to exceed coherent local oscillator laser line widths.

Only a handful of laser types practical for free-space communications links have been discovered/developed to date. Corporate and organizational investments in laser systems development have, not surprisingly, been justified on comparatively narrow grounds--the level of required investment in a single technology precludes a single firm from mounting competitive internal efforts. Individual program selections of laser types (and thus wavelength) have largely been driven by the potential of exploiting theoretical or novel laser attributes. Since free-space laser communications engineering state of the art a priori trails that of RF systems, this translates into a relatively weaker competitive position, one based upon expediency or advocacy rather than competition-motivated market optimization. This narrower laser system investment, development and product baseline should be reflected in inherently higher technical, schedule and cost risk elements for a near-term system development.

Two basic types of laser systems (externally modulated "physical" lasers, such as Nd^+:YAG, and monolithic III-V diode lasers, e.g. GaAlAs) have been proposed. Each shows tremendous promise, but a considerable expenditure of both time and resources will be required to determine if either can be systematized effectively for SDS. Significant technical drivers for both laser types have been the development of stable long-life sources and transmitter packaging (size/weight/prime power needs optimized for the operational environment).

Beam-steering requirements for SDI laser links may be accomplished either mechanically or electronically. Mechanical beam redirection involves a two-stage process: Antenna slew between platforms not in the same telescopic FOV (angles greater than 1-2 degrees) will be required for most SDI communications links. Gimballed mirror repositioning between targets offset by angles greater than a few milliradians but less than the FOV will probably also be required. Electronic (electro optic, magneto optic, etc.) steering is the alternative approach here. Whereas mechanical repositioning schemes may be satisfactory for occasional link repositioning (e.g., BSTS - BSTS), electronic beam steering with large slew angles, is probably required for those links involving SSTS and CV assets.

Diode lasers lend themselves to coherent power combining and beam sharpening through monolithic integration. Injection locking of several production-quality lasers on one monolithic substrate is

one part of the solution. Recent progress has been reported with coherent CW diode laser arrays yielding in excess of 1 watt of optical power output. However, taking such research devices to the point where they are space-qualified products is not a straightforward issue. The second solution component is electronic beam-steering circuitry. Later, monolithic integration will probably result in the all-solid-state laser transmitter. In summary, laser system state-of-the-art will continue to progress in response to advances in solid-state materials, process and fabrication technologies.

Current approaches to laser communications for space require the use of physical antenna telescopes. Monolithic laser transmitter systems (described above), functionally similar to their RF counterparts, should be demonstrated within the next three or four years. However, a monolithic ("fly's eye") receiver antenna at optical frequencies is now (and should remain for the foreseeable future) beyond the technical state-of-the-art. It is therefore not possible for us to baseline the use of all-monolithic receivers in an SDS communications hardware implementation plan. (Today, development forecasts are barely conjectural for such antennas.)

Therefore, the projected number of laser communications receiver telescopes on each SDS platform even for simplex laser links (e.g. BSTS-to-CV/SBI), will be driven by the total number of platforms to be simultaneously (rapid TDMA) internetted. The

number of monolithic laser transmitter arrays, however, would ultimately be driven by the overall SDS geometry and dynamics. (This would be similar to the EHF transmitter case.) Nevertheless, the ultimate requirement for multiple laser receiver terminals on each receiver platform would remain. Such an "open hardware architecture" feature places lasercom at a severe, probably disqualifying, disadvantage with respect to EHF.

Comparison Summary

Table X-1 summarizes the results of comparing the attributes and technical parameters of EHF and laser links. Comparisons are listed both for a "near-term" communications system (one developed using the current technical baseline) and a "mid-term" system (which allows four additional years of technology).

We judge that the technical maturity of EHF systems will today better support SDS near-term communications requirements than will laser links. EHF is still less risky for a mid-term system, although a laser technical baseline should then accommodate all but the robustness attributes. A separate receiver will be required on each platform for each simultaneous/rapid TDMA link supported. Both technologies will eventually support all SDS data rates, jam resistance, and lifetime requirements but these links would much more readily be built today at EHF.

TABLE X-1

COMPARISON SUMMARY

	1988 Cutoff	1992 Cutoff
Technical Maturity	EHF (Favored)	EHF Laser Should Meet Non-Robust Requirements
Data Rate	EHF	Both
Jam Resistance		
Overall	EHF	EHF
Power Required	Laser	Laser
Max Power	EHF	EHF
Divergence	Laser	Laser
Geometry	EHF	EHF
PAT	EHF	EHF Lasers Should Accommodate All But Fast, Large Slews
Physical		
Size & Weight	Laser*	Both***
Prime Power	Laser*	Laser***
Robustness	EHF	EHF
System Expansion	EHF	EHF
Nuclear Effects	Both**	Both**
Reliability	EHF (Better Understood)	Both (?)
Competition	EHF	EHF
Cost	EHF (Probably)	EHF

*Assumes defenses against passive countermeasures are not required.
**Depends upon laser system configuration.
***Laser RX technical breakthroughs required to support system expansion.

Lasers at much higher frequencies than EHF, would feature extremely narrow link beamwidths with sidelobes essentially confined to the vicinity of the receive platform. (For equivalent telescope/antenna quality, beamwidth scales with carrier wavelength. EHF, with wavelengths approximately 3000 times longer than diode lasers, would yield correspondingly larger beamdwidths.) Consequently, both system prime power and radiated power requirements are less for lasers than EHF (with reasonable power conversion efficiencies). However, EHF links are judged capable of higher (potentially exceeding an order of magnitude) output power--SDS constellation geometries and dynamics significantly frustrate threat jammers so that with reasonably designed anti-jamming techniques enemy jamming will be ineffective. Realization of electronically agile EHF transmit <u>and receive</u> antenna arrays with null-steering, frequency hopping and spread spectrum capabilities would render EHF the ultimate anti-jam technology choice for the foreseeable future. Due to its wider inherent beamwidth, the electronically agile EHF transmit array will require less beam steering precision and accuracy for pointing and tracking (PAT). Since such an advanced array cannot be projected for a laser receiver, in-band jamming (chiefly from aperture illumination scattering to reduce SNR or attempt command takeover C^2 functions) will remain a concern for laser links.

Lasercom hardware, some of which has been manufactured to date for experiments and demonstration programs, ought to require less

volume, weight, and power for SDI C^3 applications if a 1988 technology cutoff date were established. The inherently smaller beamwidths of lasers afford a significant prime power advantage over EHF for a single, otherwise equivalent link. The active transmit aperture at EHF is judged to require less development. When the EHF receiver is considered, vis a vis the need for several separate laser receivers, EHF communications systems are ultimately projected to assume a commanding advantage for operational SDS applications.

Nuclear effects are expected to be neutralized operationally by employing appropriate hardware and by a carefully designed operational concept, system design, development and test effort, both for EHF and laser links. Either type of link must be designed specifically to operate in stressed and disturbed environments for such technology (i.e., laboratory) developments to translate into actual military space communications capabilities. Chief areas of concern here include transient and total dose, optical and RF detector/mixer materials and circuitry, receiver amplifiers, antenna surfaces, focal plane/feed thermal effects, and performance drift of filters and phase shifter components.

Overall, there is a vigorous competitive environment for state-of-the-art EHF systems. This situation is currently fueled by a variety of military uses whose targeted applications and nuclear hardening requirements should continue the relative disparity

between EHF and lasers. Since EHF programs are proceeding apace from a broader baseline, both reliability and cost factors will continue to favor EHF developments and products for tactical and free-space communications applications.

Conclusions

In principle, EHF and laser communications systems appear potentially capable of satisfying the gross SDS communications requirements (i.e., single-link data rates over required platform separation distances). Significant concerns arise as a consequence of the large numbers of simultaneous links which may be required for robustness, the effects of inherent platform dynamics, and communications susceptibility in stressed (nuclear and jamming) environments. Overall, we judge that EHF communications systems today are more mature than lasers with respect to providing an initial capability which can evolve to satisfy ultimate SDI system requirements. Laser systems will continue to improve rapidly, thanks to microelectronic materials, processing and fabrication advances. However, solid-state EHF advances based on these same technologies will benefit at least as much as lasers from a maturing common technical baseline. We judge that EHF will thus retain a strong comparative advantage for the foreseeable future. Such lower EHF communications technical risk translates, in sequence, into lower overall schedule and cost risk elements, or alternatively, better technical performance for equal risk exposure for the overall SDS network.

The communications design philosophy which has been established for other major military and civil space projects should also be applied to the SDS communications network: It is then most efficient and cost effective, with less risk, to baseline the adoption of a single communications framework (frequencies, protocols, operational disciplines, hardware baseline, test and evaluation, activation plans, etc.) for all crosslink applications. Thus, hybrid (laser and RF) approaches do not appear advisable. The need to implement an integrated communications and battle management (BM) capability in the short term also calls into question a hybrid, joint development risk, communication architecture. Let us therefore focus our assessment on the current status and suitability of laser developments with respect to total SDS communications system requirements.

The technical baseline and competitive posture of the contractor community is more mature for EHF hardware. This translates into higher expected ability to meet technical performance, schedule and cost milestones in a development/production program. The relative robustness and growth/flexibility attributes of EHF links must also weigh heavily in a binary selection process. We also find that EHF links are likely to be present on SDS platforms to satisfy ultimate operational internetting requirements involving CV/SBI (and probable SSTS) crosslinks and space-ground up/down links. In contrast to these factors, we have the promise for lasers of lower prime power needs, enhanced

anti-jam capability (very questionable in a robust architecture) and larger available bandwidth.

Bandwidth does not appear to be at issue for the data rates envisioned in an operational SDS environment. Available EHF bandwidth allocations and hardware capabilities are sufficient. In the earlier "Comparison Summary," we concluded that EHF links can deliver the required level of anti-jam performance. Although an individual laser link will require less spacecraft prime power than an equivalent individual EHF link incorporating active arrays, this is a misleading comparison: single link pairs do not an SDS make! EHF crosslink packages, based upon electronically active array technology, have been identified and defined in this report to accommodate an open-ended expansion of the number of platforms in the overall SDS space segment.

In response to the concern that lasercom should not be so readily dismissed, we cannot in this report aim to predict the future. When projecting operational SDS communications technical postures we do not foreclose the possibility that lasercom could play a significant role. Nevertheless, we cannot identify a single SDS application for which lasercom is expected to be clearly superior. It is true that some SDS links may well be satisfied by either lasercom <u>or</u> EHF signalling. For example, where few links with little geometric/dynamic diversity are required (such as BSTS - BSTS), perhaps either alternative could be made to work. It is progressively much less advisable, however, to

consider laser links involving, in turn, SSTS, CV/SBI platforms and space-ground up/down links.

Lasercom should be developed not necessarily for SDS use, but in anticipation of future needs for extremely high free-space data rate (>20 GBPS) links and/or for links at extreme ranges (>120,000 NM). (For example, NASA deep-space probes outside the solar system may be forced to adopt optical links for data relay back to the Earth.) We conclude, however, on balance that EHF communications links are preferred over laser links for all SDS communications applications.

Recommendations

We recognize the critical role of C^3BM/C^3 countermeasures (CM) as a fundamental SDS system acquisition driver. Recommended here are capable and survivable system mission links ensuring mission accomplishment through robust performance. It is most critical to immediately implement a strong C^3BM/C^3CM program thrust. An integrated, highly visible SDS C^3 development office, managed both to aggressively exploit the evolving technical state of the art and to enforce communications architecture discipline will contribute significantly to near and far term SDS viability.

Achievement of such communications system hardware will require a focused EHF development program. Hardware design and development programs for each link should begin immediately build upon near term system performance simulations. Critical supporting technical demonstrations of efficient low-loss power combining and electronically agile transmit and receive arrays are needed early in the program. These should exploit recently demonstrated successes with like efforts at Ku-band and the applications state-of-the-art in advanced MMIC/MIMIC III-V technologies.

So that efficient system upgrade planning is incorporated a priori, we recommend vigorous C^3 program office sponsorship of appropriate relevant advanced technologies. Applications-oriented research and development of mid-upper EHF and high-payoff lasercom technologies will provide the basis for efficient and cost-effective system block changes. Once operational, the SDS C^3 network size and complexity could effectively deter attempts to upgrade it. In this context, a modest amount of margin ought to be designed into, and reserved for, the pre-planned product improvement (P^3I) of communications on board all SDS spacecraft. More advanced capabilities, once proven in the laboratory, could then be configured for and experimentally demonstrated in the operational SDS environment prior to commitment to any C^3 system upgrade. FOV and external viewing placement are critical components of such reserved margin.

EHF is the frequency band recommended for all SDS links. Space-to-space communications operation in the O_2 band at 58-62 GHz should be baselined for critical mission link protection from ground and airborne jamming threats. Lower millimeter wave (MMW) frequencies are most appropriate for up/down links at this time. To fully realize the weight, prime power advantage, and narrow beamwidth advantages of higher MMW frequencies, we recommend planning to move to mid-EHF (100 GHz) at least for up/down links as the technical base and platform internetting requirements become more firmly established. Careful upgrade planning with associated technical/investment emphasis is essential to survivable SDS mission links as both domestic and threat capabilities evolve.

XI. SUMMARY

SUMMARY

A robust communications architecture was described to provide the background for the overall security of the SDI/SDS Program. The angular diversity provided by this satellite-to-satellite communications architecture, coupled with the dynamic nature of each node, assures system connectivity and renders jamming to be virtually useless. The robust angularity of the parallel linkages also helps alleviate disruption from nuclear events. Electronically-agile antennas are at the heart of this architecture and, in the EHF band, remain the only significant technology that requires heavy emphasis--these devices are in the laboratory at 20 GHz and 44 GHz, and development at 60 GHz has begun. Resources to space-qualify the systematization of these devices also exist, but more emphasis is required to guarantee their timely availability for SDI/SDS.

The BER and link-margin advantages associated with multiple independent links are clearly demonstrated, even accepting just the simple analysis here, but hard, numerical descriptions of the actual SDS geometry are both 1) expected to be better than the numbers shown here, and 2) in need of considerably more analysis than available in this study.

The penalties associated with guaranteeing connectivity as described in this architecture are higher data rates (generally

more bursts, not necessarily more data per burst) and more capable antenna systems. The data rates are currently achievable, and the antenna systems for EHF are in development, as described earlier. The comparable laser antenna systems with fast, large slews are not available in the near future; and regarding lasercom receivers, may not be available for SDS at any time in the foreseeable future. For some links, most notably BSTS-BSTS, robustness cannot be increased dramatically and lasers are more feasible than they are for other links; however, a laser/EHF hybrid communications system would pay severe size and weight penalties and it is recommended that as long as one technology can support all the links, that SDS stay with one technology. Other links gain significantly from the multiple routing of information.

In the long term lasers may have unique advantages that can be effectively exploited: very narrow beamwidths (though in some cases, may be too narrow), the physical capacity to handle extremely large data rates, and possible size/weight/prime-power advantages. Laser reliability involves many unknowns and trade offs associated with systematizing the laboratory technology need much more development. Also, certain potential vulnerabilities, especially relatively inexpensive passive countermeasures, require further analysis--a laser communications system that would have to address such vulnerabilities could suffer very significant size/weight/power penalties.

An EHF/laser comparison was treated with considerable depth, and at this point it is recommended that both technologies be supported. However, in the near term, plan for EHF links. In any case, do not underestimate the value of robustness or overestimate the penalties associated with its implementation.

Further analysis is required to determine how best to exploit SDS's robust geometry and the advantages of satellite-to-satellite relaying of information. If sensor information penetrates to any satellite within the CV/SBI constellation (clearly a certainty), then a properly constructed inter-orbit netting of links will guarantee connectivity in the most severe jamming and nuclear environment. Some educated guesses as to more desirable choices of robust netting schemes were included here, but more study is required.

Finally, with the multitude of SDI/SDS thrusts currently in being, a government or government-sponsored focal point for communications architecture is essential to the successful integration of all information nodes. The robust advantages inherent in the SDS geometry can only be exploited with an harmonious architecture supported within each element.

APPENDICES

A. WORLD SITUATION SET

(Developed by the SDI Phase 2 Architects and the AF Architects During Phase 2 Project Convergence)

PROJECT CONVERGENCE October 18, 1987

WORLD SITUATION SET AND SYSTEM COMPARISON CONSTRAINS
Version 1.1

I: WORLD SITUATION SET:

1. THREAT

1 Inventory

1.1 Offensive Object Count

Boosters:	900	(ICBM's & SLBM's)
ASAT's	500	(?)
Post Boost Vehicles	3,500	
Re-Entry Vehicles	8,500	
Decoy A's	85,700	
Decoy B's	100,000	
Debris	100,000	(Mid-Course Sensor Study)
Total:	298,100	

Excursion: 180,000 Decoy B's in lieu of 50,000 Decoy A's
Delta 130,000
Total 428,100

2. DEFENSIVE

2.1 JAMMERS

- Frequency Band:
  44/20 Ghz: MILSTAR Threat
  60 GHZ: As described below.

2.1.1 NEAR EARTH CARRIERS: ≤ 40 aircraft; 80-90% flying during attack.
Parachute - No
Sea Based: Not for 60 Ghz Band.
Land Based: Not for 60 Ghz Band

2.1.1.1 Power Generation:
Aircraft: 200 kw average RF power, at 10% prime to RF power efficiency (Total for one aircraft)
Sea Based: MILSTAR threat, only
Land Based: MILSTAR threat, only

2.1.1.2 Antenna Diameter: ≤ 1 Meter, ≤ 2 per aircraft
Antenna Switching: Ok, consistent with rf power generation limitations, and increased transmission loss.
Transmission Losses: 2.0 dB with no switches and only one power source.
Pointing capability: Open loop pointing based on orbital parameters only. 1 dB pointing loss.

2.1.1.3 Jamming Signal Structure:

Frequency: a. Worst Case for particular modulation structure, when jammer happens to be in the signal band.

b. Band choice: Limited by ability to intercept signals, and to decide what band(s) to use for the receiver(s) to be jammed.

c. Multiple frequencies: ok, but total average power in all frequencies is $\leq$ 200 kw, average.

d. Number of simultaneous frequencies from a particular aircraft is fixed; maximum power for one frequency is limited to the average power divided by the number of frequencies for that aircraft. (No dual mode transmitters)

e. Reference Design: 10 rf power sources @20 kW. or 1 at 200kW

Jammer Signal Structure: Worst case for particular modulation structure; CW or pulsed for Project Convergence (Ability of power gyratron power sources to operate in pulse mode TBD).

Pulsing Characteristics: Duty Cycle: * Tech. Survey
Pulse duration:
Pulse Interval:
Repetition Rate: Uniform.

Bandwidth Range Available: 2 Ghz

Tunability: Limited to bandwidth range

2.1.1.4 Deployment Location:

- Aircraft: Within 500 nm of Soviet controlled territory, at altitudes $\leq$ 20 km.
- Land & Sea based: MILSTAR threat

2.1.1.5 Design Approaches:

- Design for the following cases:
  - No Jamming
  - Minimum Allowable Range = Satellite Altitude or
  - Minimum Allowable Range = 1,000 and 2,000 km.

2.1.2 SPACE BASED JAMMERS

Jamming Satellites: $\leq$ 36 (TBR)

2.1.2.1 Power Generation:

- Hi energy density batteries:
  - Maximum Battery Weight: $\leq$ 2,000 lb.
  - Type A: LiH @ 13 Wh/lb
  - Type B: NaS @ 50 Wh/lb
  - Total assumed power capacity: 26,000 Watt-Hours based on type A batteries.
- $\leq$ 5.2kw average RF power, at 10% battery to RF power efficiency (Total power per spacecraft); 30 minutes battery duration.

2.1.2.2 Antennas

Diameterr: a. ≤ 3 Meter, ≤ 3 per jamming spacecraft or
b. ≤ 1 Meter, ≤10 per jamming spacecraft or
c. ≤ .1 Meter, ≤ 64 per jamming spacecraft

Switching: Ok, consistent with rf power generation limitations, and increased transmission loss.

Transmission Losses: 2.0 dB with no switches and only one power source.

Pointing capability: Open loop pointing based on orbital parameters only; 1.0 dB pointing loss.

2.1.2.3 Jamming Signal Structure:

Frequency: a.Worst Case for particular modulation structure, when jammer happens to be in signal band.
b.Band choice: Limited by ability to intercept signals, and to decide what band(s) to use for the receiver(s) to be jammed.
c.Multiple frequencies: ok, but total average power in all frequencies is ≤ 5.2 kw, average.
d.Number of simultaneous frequencies from a particular spacecraft is fixed; maximum power for one frequency is limited to the average power divided by the number of frequencies for that spacecraft.
e. Reference design: 10 power sources @ 520 watts

Jammer Signal Structure: Worst case for particular modulation structure; cw or pulsed for Project Convergence

Pulsing Characteristics: Duty Cycle: *Tech survey
Pulse duration:
Pulse Interval:
Repetition Rate: Uniform.

Bandwidth Range Available: 2 Ghz

Tunability: Limited to bandwidth range.

2.1.2.4 Deployment Location:

- Any altitude ≤ 2,000 km above SSTS for above power levels.
- Any altitude ≥ 2,000 km above SSTS for power levels not to exceed 30% of the above power levels.
- Worst case for satellite whose receivers are to be jammed.

2.1.2.5 Design Approaches

- Design three cases, as follows:
  - Reference: No jammers
  - With Jammers; Minimum Allowable Range = 1,000 km
  - With Jammers; Minimum Allowable Range = 500 km.

2.1.3 ROCKET BASED JAMMERS

Number of Rockets: None; considered to be impractical.

2.1.3.1 Power Generation:

≤ 1kw average RF power, at 10% prime to RF power efficiency

2.1.3.2 Antennas

Diameter: a. ≤ 1 Meter, ≤2 per rocket or
b. ≤ .1 Meter, ≤ 10 per rocket

Switching: Ok, consistent with rf power generation limitations, and increased transmission loss.

Transmission Losses: 2.0 dB with no switches and only one power source.

Pointing capability: Open loop pointing based on orbital parameters only; 1.0 dB pointing loss.

2.1.3.3 Jamming Signal Structure:

Frequency: a. Worst Case for particular modulation structure, when jammer happens to be in signal band.
b. Band choice: Limited by ability to intercept signals, and to decide what band(s) to use for the receiver(s) to be jammed.
c. Multiple frequencies: ok, but total average power in all frequencies is ≤ 1 kw, average.
d. Number of simultaneous frequencies from a particular spacecraft is fixed; maximum power for one frequency is limited to the average power divided by the number of frequencies for that spacecraft.

Jammer Signal Structure: Worst case for particular modulation structure; cw or pulsed for Project Convergence

Pulsing Characteristics: Duty Cycle: *Tech survey
Pulse duration:
Pulse Interval:
Repetition Rate: Uniform.

Amplifier Bandwidth Available: 2 Ghz

Tunability: Limited to amplifier bandwidth

2.1.3.4 Deployment:

Launch Site: Any ship or submarine further than 100 nm from CONUS.

Trajectory: Similar to ERIS, GSTS etc, but with parachute type descent during reentry.

2.1.3.5 Tactics: Deployment of this type of jammer in lieu of an equivalent number of ballistic missiles is questionable.

2.2. NUCLEAR EFFECTS

2.2.1 COMMUNICATIONS SUPPRESSION

2.2.1.1 Type A: SPACE TO CONUS COMMUNICATIONS DISRUPTION

Depressed trajectory SLBM launches simultaneously with ICBM launch, in order to introduce defense suppression and high altitude nuclear bursts for communications disruption.

2.2.1.1.1 Number of launches:12 per Submarine; 2 submarines

2.2.1.1.2 Launch locations: one off of the east coast, one off of the west coast.

2.2.1.1.3 Intended burst locations:

a. CONUS fixed SDS Control Centers

b. 200 km bursts distributed over CONUS as illustrated in the attached CONUS figure.

2.2.1.2 Type B: Boost Battle Space:

Communications suppression nuclear bursts over the Soviet Unión concurrent with other booster launches.

2.2.1.2.1 Burst Locations:

- Distributed equally over a 2,000 x 3,000 directly over the Soviet Union per attached figure.
- Altitude: Most Effective; nominally 250 kM.

2.2.1.2.2 Number of Bursts: 60 in each of two waves separated by two minutes, with the first launch concurrent with first ICBM booster launch.

2.2.1.3 Type C - Midcourse Battle Space

Communications suppression nuclear bursts over the polar region.

2.2.1.3.1 Burst Locations:

- Distributed equally over a 2,000 x 3,000 directly over the Soviet Union per attached figure.
- Altitude: Most Effective; nominally 250 kM.

2.2.1.3.2 Number of Bursts: 60 in each of two waves separated by two minutes, with the first launch concurrent with arrival of first ICBM booster.

2.2.2 ASAT`s

2.2.2.1 General: Directly ascent missiles attacking CV's and SSTS satellites launched from Soviet landmass.

2.2.2.2 Number of launches: 200 total, 4 per SDS target, one command detonated.
(Based on approximately 25 -50 useful CV's to attack).

2.2.2.3 Detonation location: Within 2000 km of Soviet Landmass.
primarily distributed along CV orbital locations, 16 to the north, 8 to the south at CV altitude.
Note: SSTS are believed to be too far away for an attack to be effective. (20 minutes time of flight?)

2.2.3 ICBM SALVAGE FUZING
Considered to not be practical for all multi-RV ICBM's(fratricide issue), and to be time delayed for single RV ICBM's until South of 70 degrees North Latitude.

Total number: ≤ 50

2.2.5 Space Mines: Negated in peacetime with the aid of in-situ inspection.

2.2.3 Effect of Nuclear Bursts on Communications:
Yield: ≤ 1 Mt each
Affected Area: 100,000 kM2 for two minute period.
(Circular region 350 kM(194 nm) in diameter)
Burst Coupling: Each burst is considered to be sufficiently far apart that coupling does not occur.
Effect on communications:
- Introduces Rayleigh fading only.
- Antenna Temperature Increase: ≤ 100°K over background.
- Increased Path Attenuation: ≤ .4 dB at 60 Ghz
≤ .5 dB at 30 Ghz
≤ .7 dB at 20 Ghz
- Antenna Angle of Arrival Losses: ≤ .1 dB at 60 Ghz
≤ .2 dB at 40 Ghz
≤ .3 dB at 20 Ghz

3. CONSTRAINTS

This section is intended to address limitations imposed by practical design/launch weight limitations.

3.1 Prime Power for BMC3 FUNCTIONS(Battle Management + Communications)
Prime Power requirements shall be generated for the platforms listed below that include all non-sensor processing required for BMC3. It shall include power needed to accomplish track association, stereo tracking, discrimination of all targets not known apriori, communications message processing and routing, threat propagation and evaluation, weapon assignment, fire control commanding, weapon guidance, and BMC3 administration and control(software, testing, C&C etc) and all communications receive/transmit functions.

BSTS, SSTS, SBI-CV, SBI-KKV, ERIS AND GSTS

Fault-tolerance and non-volatile memory for critical functions (eg,timing, tracking filter covariances, critical programs and data base parameters) shall be provided.

Traceability shall be provided to support/justify the values used to generate the totals. Analysis and supporting rationale shall be generated to support the values used for items not yet in existence.

These estimates shall not include additional power required for environmental control when not operating. However, if dual systems are provided, both shall be powered up 25 minutes prior to expected use.

3.2 Weight for BMC3 FUNCTIONS(Battle Management + Communications)
Weight estimate shall be generated for the platforms listed below that include all non-sensor processing required for BMC3. It shall include weight of the processors needed to accomplish track association, stereo tracking, discrimination of all targets not known apriori, communications message processing and routing, threat propagation and evaluation, weapon assignment, fire control commanding, weapon guidance, and BMC3 administration and control(software, testing, C&C etc) and all communications receive/transmit functions including TT&C, GPS and time reference/base oscillators and clocks.

BSTS; SSTS, SBI-CV, SBI-KKV, ERIS AND GSTS

Fault-tolerance and non-volatile memory for critical functions (eg,timing, tracking filter covariances, critical programs and data base parameters) shall be provided.

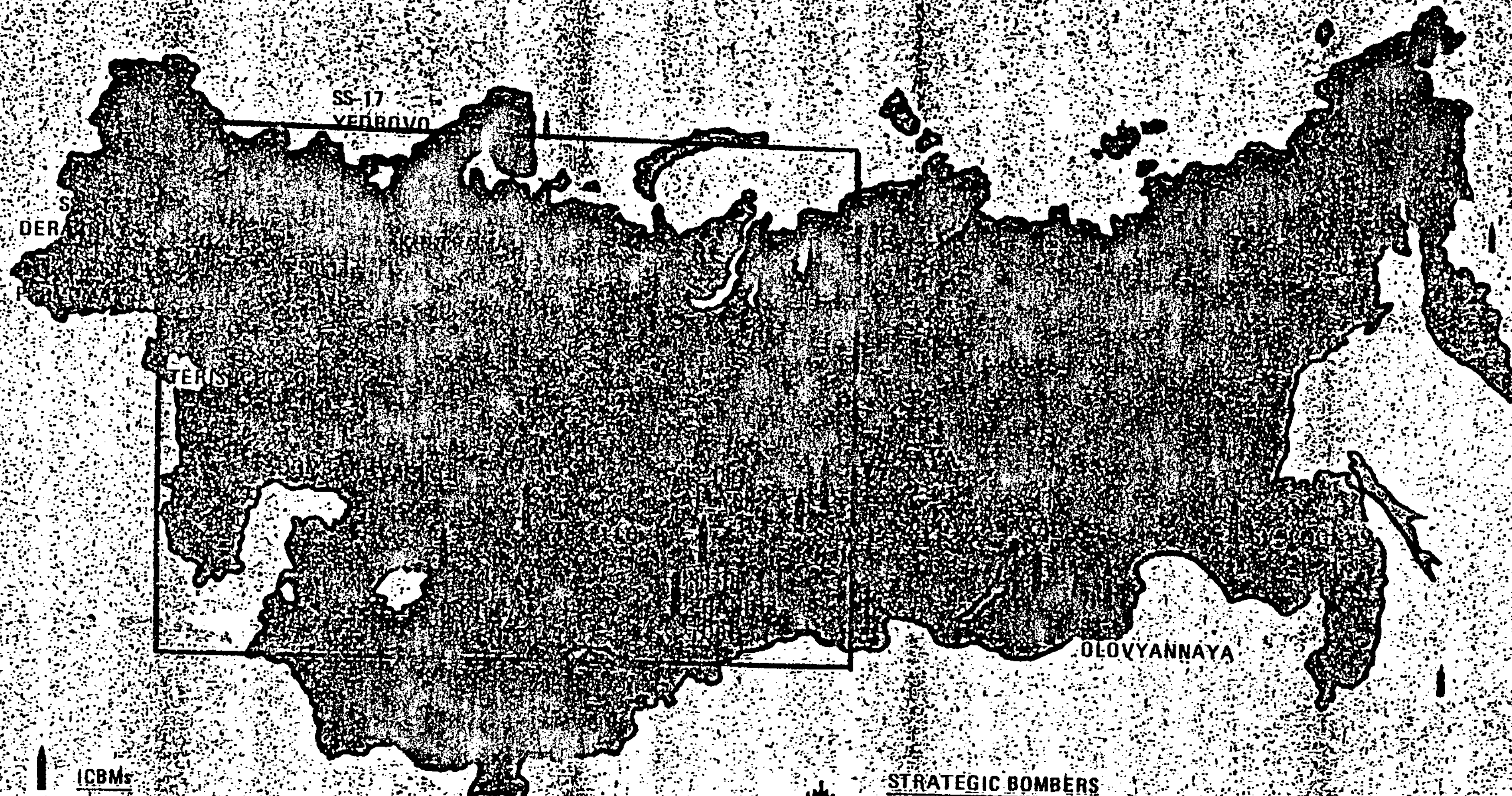
Traceability shall be provided to support/justify the values used to generate the totals. Analysis and supporting rationale shall be generated to support the values used for items not yet in existence.

These estimates shall not include additional weight required for environmental control, or power generation; ie, equipment shall be assumed to be mounted within the host spacecraft except for transmitters that must be mounted above antenna gimbals (between the gimbals and the antennas).

E1013

Strategic Nuclear Forces

CASE 1 DISRUPT BOOST PHASE COMMUNICATIONS



ICBMs

SS-11	550
SS-13	60
SS-17	150
SS-18	308
SS-19	330

LRINF*

SS-4	232
SS-5	16
SS-30	333

*NOT DEPICTED

SLBMs

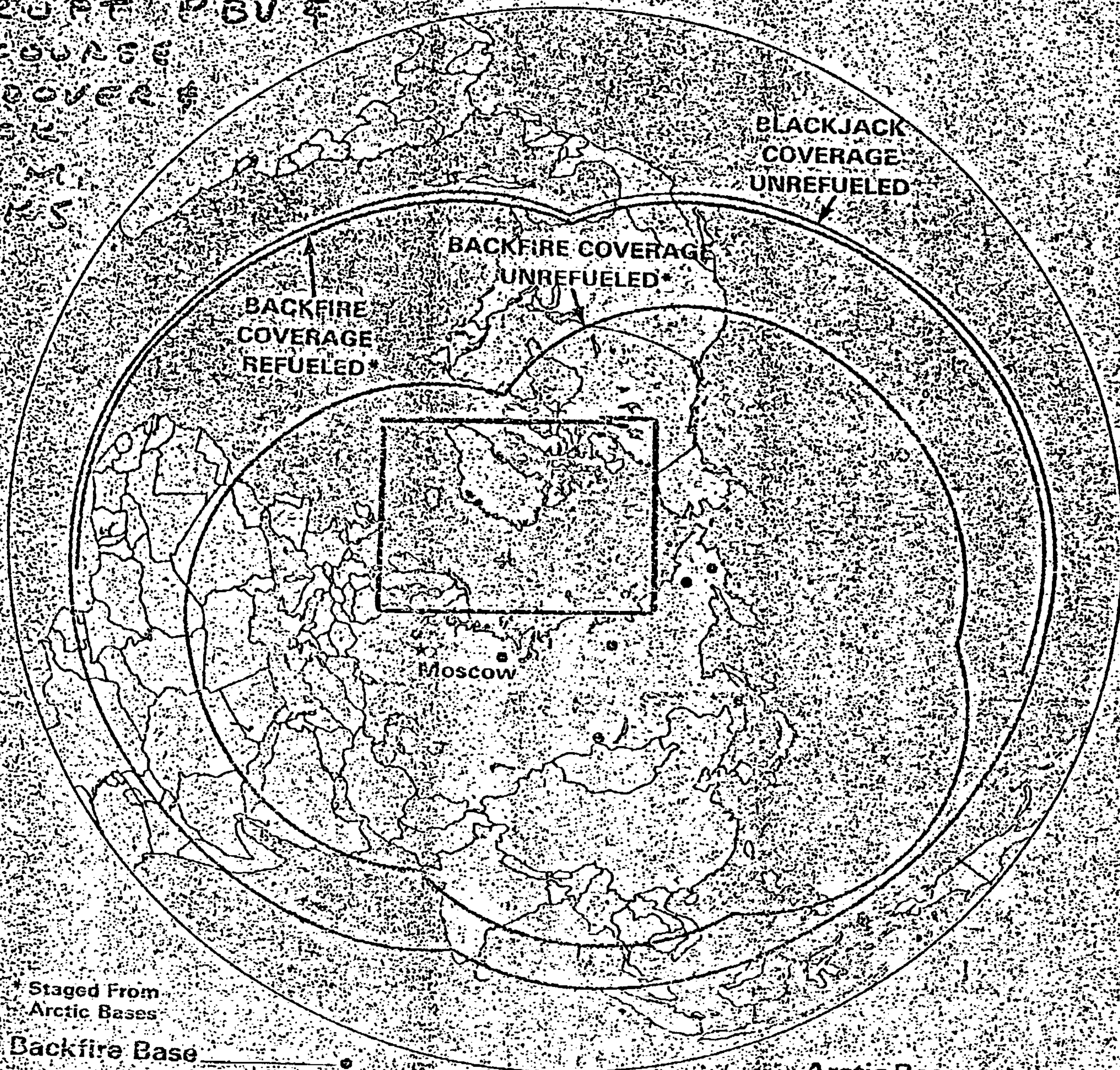
SS-N-6
SS-N-8
SS-N-17 } 950+
SS-N-18
SS-NX-20

STRATEGIC BOMBERS

BACKFIRE	200+
BISON	45
BEAR	100
BADGER/BLINDER	455

CASE 2 -
DISRUPT PBV &
MIDCOURSE
HANDOVER &
TRACK
COMM
LINKS

Blackjack and Backfire Coverage from Soviet Bases
(2-Way Missions)



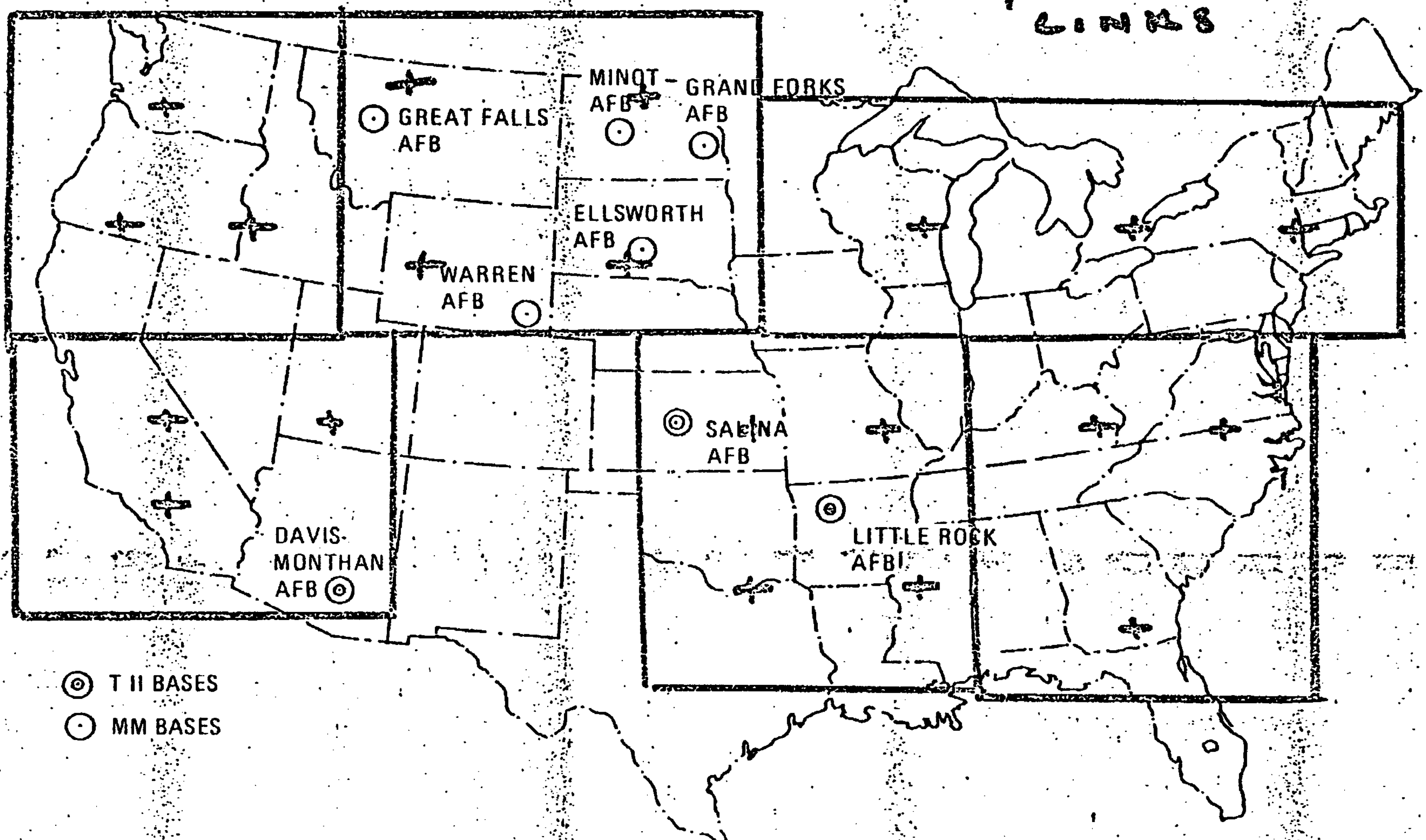
* Staged From Arctic Bases

Backfire Base

Arctic Base

Map of ICBM Locations

CASE 3 - DISRUPT ERIS & GSTS COMM. LINKS



B. PROPAGATION THROUGH A NUCLEAR-PERTURBED ENVIRONMENT

PROPAGATION THROUGH A NUCLEAR-PERTURBED ENVIRONMENT

(NOTE: The majority of this appendix is excerpted from private communications with Dr. Peter Monsen, a consultant in this study, as well as two published works: A Trans-Ionspheric Signal Specification for Satellite C^3 Applications, by Dr. Leon Wittwer (DNA Report #5662D, dated 31 December 1980) and Fading Channel Communications, by Dr. Monsen (IEEE Communications Magazine, dated January 1980).

The SDS architecture consists of the following terminals:

1) BSTS
2) SSTS
3) CV/SBI
4) GEP
5) ERIS
6) GSTS

Communication between these terminals is to be maintained when exposed to the EW and nuclear environment outlined in the WSS (Appendix A). To accomplish this, a hybrid direct sequence/frequency hopping (DS/FH) form of modulation operating in a burst mode is assumed with all of the 10% available emission bandwidth used for spreading. It is recognized that it may in some instances be impractical to obtain all of the processing gain via spreading and that a combination of spreading and sidelobe cancelling may have to be employed. Further, to operate near optimally in the fading environment imposed by the nuclear threat, it will be assumed that coherent demodulation will be used for data rates greater than 500Kb/s and noncoherent techniques utilized for data rates less than 500 Kb/s.

The following frequency bands are presumed for the various links:

1) Satellite-to-Satellite 60 GHz

2) Uplink 44 GHz

3) Downlink 20 GHz

It will be assumed that an optimized jammer is employed which, due to the countermeasures utilized, is a broadband noise jammer. The scintillation channel will be presumed to be endowed with the following types of disturbances:

1) Fading
2) Multipath
3) Scattering
4) Absorbtion
5) Antenna Temperature Increase

The communication channel perturbed by nuclear bursts is modeled as a linear channel possessing a time varying impulse response.

Thus,

$$R(t) = \int_0^\infty d\tau \; h(t,\tau) \; S(t-\tau) \tag{1}$$

Where,

$S(t)$ = transmitted signal

$R(t)$ = received signal (complex number representation)

$h(t,\tau)$ = channel impulse response function

The specification channel impulse response functions:

$$h(t,\tau) = A(t)\exp\left[i\frac{2\pi f_c z(t)}{c} - i\frac{cr_o N(t)}{f_c}\right]\int_{-\infty}^{\infty} d(\Delta f)\; \tilde{h}_s(t,\Delta f)$$

$$\exp\left[-i\frac{cr_o N(t)\Delta f^2}{f_c^3} - i2\pi\Delta f\left(\tau - \frac{z(t)}{c} - \frac{cr_o N(t)}{2\pi f_c^2}\right)\right] \tag{2}$$

Where,

f_c = carrier frequency (hz)

c = light speed (3×10^8 m/sec)

$z(t)$ = propagation path length (m) (2)

r_o = classical electron radius (2.82×10^{-15}m)

$N(t)$ = total electron content (m^{-2})

For other than circular polarization, Equation 1 should be applied to each polarization state and N(t) used to calculate the Faraday rotation effects.

$$A(t) = \exp(-0.115K_A)\left[\frac{1}{G(0)}\int_0^{\pi} d\theta \frac{G(\theta)\theta}{\sigma_\theta^2} \exp(-\theta^2/2\sigma_\theta^2)\right]^{\frac{1}{2}} \tag{3}$$

K_A = absorption (dB)

$G(\theta)$ = antenna gain function

σ_θ^2 = energy angle of arrival variance (rad^2)

$$\tilde{h}_s(t,\Delta f) = \int_{-\infty}^{\infty} d\tau \int_{-\infty}^{\infty} df\ h_s(f,\tau)\exp(i2\pi\Delta f\tau + i2\pi ft) \tag{4}$$

Equation 3 assumes that the transmitter is on the antenna axis and that the antenna pattern is cylindrically symmetric about that axis. If the threat has amplitude fluctuations (always assumed Rayleigh), then $h_s(f,\tau)$ is a zero mean normally distributed random variable with an autocovariance defined by

$$\overline{h_s^*(f,\tau)h_s(f',\tau')} = \delta(f-f')\delta(\tau-\tau')\Gamma_2(f,\tau) \tag{5a}$$

$$\overline{h_s(f,\tau)h_s(f',\tau')} = 0 \tag{5b}$$

where $\Gamma_2(f,\tau)$ is the generalized power spectrum and δ (x-x') is the Dirac delta function defined for any function f(x) by

$$\int_{-\infty}^{\infty} dx\ \delta(x-x')f(x) = f(x')$$

The generalized power spectrum is parameterized by τ_o, the scintillated signal decorrelation time, and f_o, the frequency selective bandwidth. There are two forms for the generalized power spectrum depending on the product $f_o T$ where T is the minimum symbol period. For $f_o T>1$

$$\Gamma_2(f,\tau) = \frac{1.864\tau_o\delta(\tau)}{\left[1+8.572\tau_o^2 f^2\right]^2} \tag{6}$$

This represents the flat fade condition with respect to the symbol period, T. For $f_o T \leq 1$

$$\Gamma_2(f,\tau) = 2^{3/4}\pi^{1/2}\frac{f'\tau_o}{C_1^{1/2}}\exp\left\{-\frac{1}{2C_1^2}\left[(\pi f\tau_o)^2-2\pi f'\tau\right]^2-(\pi f\tau_o)^2\right\}$$

$$\int_{-\infty}^{\infty} dx\ \exp\left\{-x^4-2x^2\left[\frac{C_1}{2^{1/2}}\left(1+\frac{1}{C_1^2}\left((\pi f\tau_o)^2-2\pi f'\tau\right)\right)\right]\right\} \tag{7}$$

where

$f' = f_o(1+C_1^2)^{1/2}$

C_1 = delay parameter (=0.25)

For both equation 6 and 7

$$\int_{-\infty}^{\infty} df \int_{-\infty}^{\infty} d\tau \ \Gamma_2(f,\tau)=1 \tag{8}$$

Equation 7 provides for scintillation random delay or, equivalently, frequency selective effects.

If there are scintillations for any kind, then there is a random time varying component in N(t) in addition to the very large scale (slow) variations.

The total electron content is

$$N(t) = N_L(t)+\int_{-\infty}^{\infty} df \ g(f)\exp(-i2\pi ft) \tag{9}$$

where $N_L(t)$ is the large scale (slow) component and g(f) is a zero mean normally distributed variable representing the random component. The autocovariance of g(f) is

$$\overline{g^*(f)g(f')} = \delta(f-f')\frac{\tau_o(f_c/r_o c)^2}{\left[a^2+(2\pi f\tau_o)^2\right]^{3/2}}, \quad f\leq f_R$$

$$= 0, \quad f>f_R \tag{10}$$

where

$$g(f) = g^*(-f)$$

$$a^2 = \left(\frac{r_o c N_L(t)}{f_c}\right)^{-2}$$

f_R = Rayleigh frequency

With the specification of K_A, σ_θ^2, $N(t)$, τ_o, f_R, f_o, and $z(t)$, we obtain a complete description of the disturbed signal as determined by the propagation environment and system geometry. $G(\theta)$ is supplied by the user independent of the environment and geometry.

The following scintillation parameters were used for the link margin analysis described in Section VI:

	Ground-Space Links	Space-Space Links
τ_o	0.04 msec	0.08 msec
fo	2.6 MHz	4 MHz
2 drms	122 NS	7.8 NS
Ant Scattering Loss	21.1 dB	15.1 dB
Absorption	4.8 dB	1.1 dB
Temp	8900°K	4000°K

Several variables which are important in the design of communication links when attempting to mitigate the effects of nuclear bursts are delineated below:

Data Bandwidth	R_B
Signal/Noise Ratio	E_B/No
Multipath Spread	$d_{rms} = \dfrac{1}{2\pi\, fo}$
Doppler Spread	$f_{rms} = \dfrac{1}{2\pi\, \tau o}$
Receiver Bandwidth	B

Small Data Bandwidth (NO Intersymbol Interference [ISI])	$R_B << 1/drms$
Large Data Bandwidth (ISI)	$R_B \sim 1/drms$

To mitigate fading a combination of frequency spreading, Forward Error Correction (FEC), and interleaving is typically used. The effect of direct sequence modulation on fading is easily summarized. Suppose a pseudo noise (PN) sequence is used with chip time T_c seconds. Then, time selective fading occurs when the channel changes in less than T_c seconds.

Frequency selective fading occurs when received frequencies in signal band have decorrelated fading and are separated by less than BHz. To mitigate both effects use DS modulation with $T_c << \tau_o$.

Frequency selective fading also gives rise to the following two cases:

<u>Case 1</u>

$B > B_C > R_B$

Implicit Diversity

NO ISI

<u>Case 2</u>

$B > R_B \gtrsim B_C$

Implicit Diversity

ISI

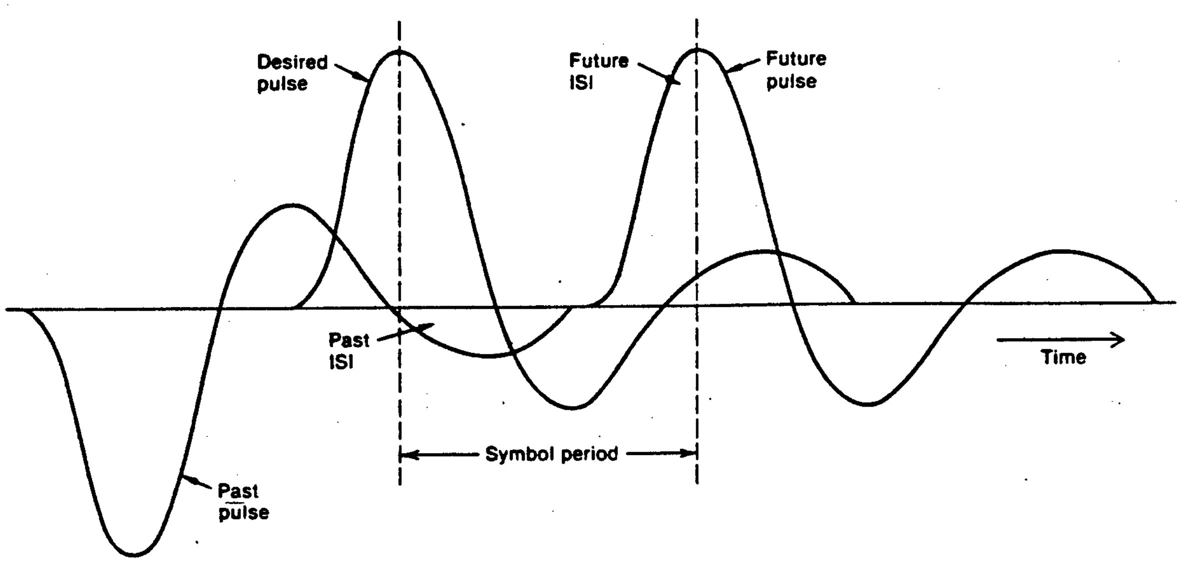
To mitigate any resulting ISI, equalization techniques are employed. Adaptive equalizers have been demonstrated which are efficiently able to detect digital signals perturbed by a fading channel medium while tracking the fading variations. If adaptation requires significantly less signal-to-noise ratio per bit than conventional detection of the digital signal, the decisions can be effectively used as the estimate of the transmitted signal to achieve what is referred to as decision-directed adaptation. Such systems can be operated without transmission of special pilot or reference signals for channel tracking. In troposcatter communication, adaptive techniques have increased the digital rate capability by at least an order of magnitude.

A linear equalizer (LE) is defined as an equalizer which linearly filters each of the N explicit diversity inputs. An improvement to the LE is realized when an additional filtering is performed upon the detected data decisions. Because it uses decisions in a feedback scheme, this equalizer is known as a decision-feedback equalizer (DFE).

The operation of a matched filter receiver, an LE, and a DFE can be compared from examination of the received pulse train example of Figure 1. The binary modulated pulses have been smeared by the channel medium producing pulse distortion and interference from adjacent pulses. Conventional detection without multi-path protection would integrate the process over a symbol period and

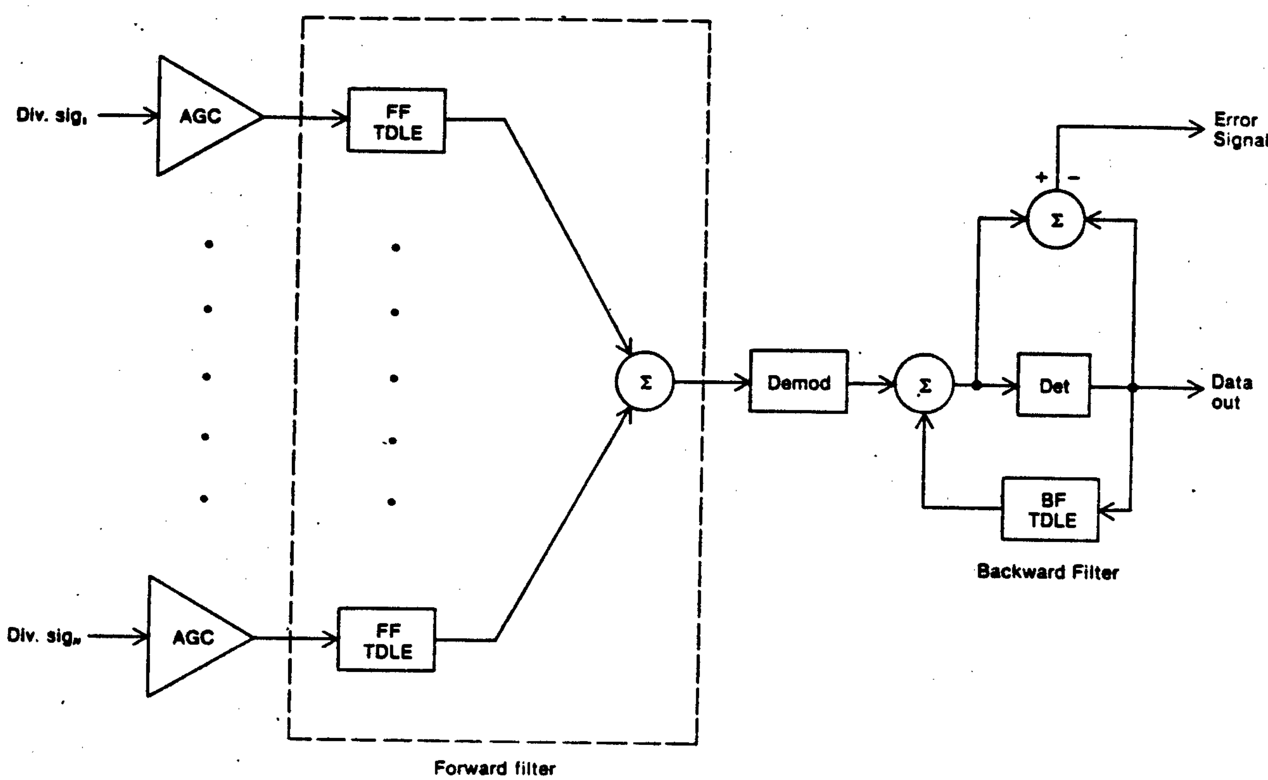
decide a +1 was transmitted if the integrated voltage is positive and -1 if the voltage is negative. The pulse distortion reduces the margin again in that integration process. A matched filter correlates the received waveform with the received pulse replica thus increasing the noise margin. The intersymbol interference arises from both future and past pulses in these radio systems since the multipath contributors near the mean path delay normally have the greatest strength. This ISI can be compensated for in a linear equalizer by using properly weighted time shifted versions of the received signal to cancel future and past interferers. The DFE uses time shifted versions of the received signal only to reduce the future ISI. The past ISI is cancelled by filtering past detected symbols to produce the correct ISI voltage from these interferers. The matched filtering property in both the LE and DFE is realized by spacing the taps on the TDLE at intervals smaller than the symbol period.

Figure 1. Received Pulse Sequence After Channel Filtering



The DFE is shown in Figure 2 for an Nth order explicit diversity system. A forward filter (FF) tapped delay line equalizer (TDLE) is used for each diversity branch to reduce correlated noise effect, provide matched filtering and proper weighting for explicit diversity combining, and reduce ISI effect. After diversity combining, demodulation, and detection, the data decisions are filtered by a backward filter TDLE to eliminate intersymbol interference from previous pulses. Because the backward filter compensates for this "past" ISI, the forward filter need only compensate for "future" ISI.

Figure 2. Decision-Feedback Equalizer, Nth-Order Diversity



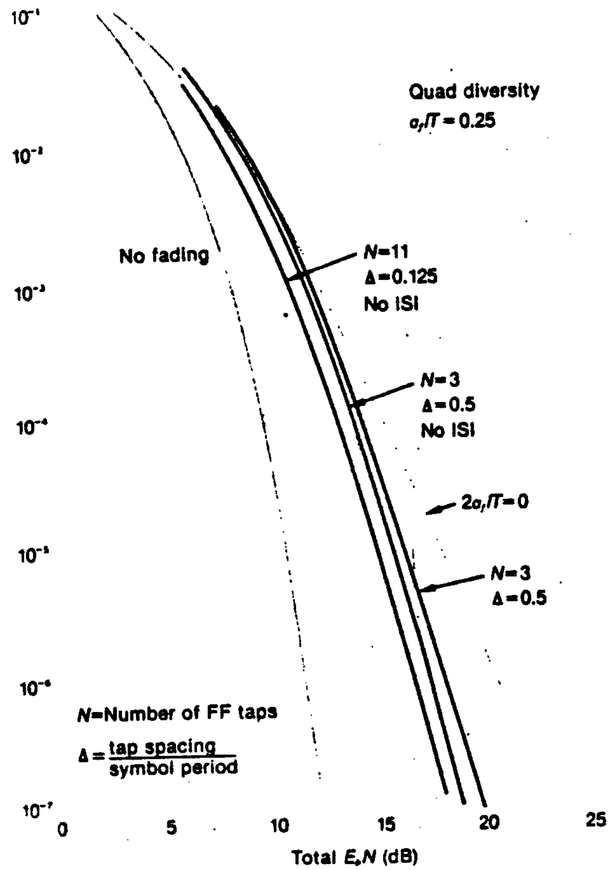
An automatic gain control (AGC) amplifier is shown for each diversity branch in order to bring the fading signal into the dynamic range of the TDLE. A decision-directed error signal for adaptation of the DFE is shown as the difference between the detector input and output. Qualitatively one can see that if the DFE is well adapted this error signal should be small. Reference-directed adaptation can be accomplished by multiplexing a known bit pattern into the message stream for periodic adaptation.

When error propagation due to detector errors is ignored, the DFE has the same or smaller mean-square error that the LE for all channels. The error propagation mechanism has been examined by a Markov chain analysis and shown to be negligible in practical fading channel applications. Also in an Nth order diversity application, the total number of TDLE taps is generally less for the DFE than for the LE. This follows because the former uses only one backward filter after combining of the diversity channels in the forward filter.

The performance of a DFE on a fading channel can be predicted using a transformation technique which converts implicit diversity into explicit diversity and which treats the ISI effects as a Gaussian interferer. As an example, the average probability of error versus the total received bit energy (E_b) relative to the noise spectral density (N_o) is shown in Figure 3 for a quadruple diversity system. The dashed line represents the

zero multipath spread (σ_f = 0) performance and the solid lines show performance for different DFE configurations (N - number of forward filter taps and Δ = normalized tap spacing) and ISI conditions when the ratio of multipath spread to symbol period T is 0.25. The no-ISI conditions are performance bounds determining by setting the ISI components to zero. When σ/T = 0.25, performance would be to the right of the dashed line if adaptive signal processing were not employed. The equalizer is seen to remove this degradation and also provide an implicit diversity gain which is measured by the difference between the solid line N = 3, Δ = 0.5 curve and the dashed line. The difference between the N = 3, Δ = 0.5 curve and the next curve labeled "No ISI" is the intersymbol interference penalty. With the filter parameters N = 3, Δ = 0.5, no technique for removing ISI can do better than this curve. The small-ISI penalty in this typical example is a strong argument for the use of the DFE versus more powerful ISI techniques. Finally the leftmost solid line approximates the very best that can be done as results show negligible improvement as the number of taps is increased further. The small difference exhibited shows that a DFE with only a modest number of forward filter taps performs to an ideal DFE with an infinite number of taps.

Figure 3. DFE Performance, Quad Diversity



Error correcting may be utilized to mitigate the effects of fading as well as pulsed jamming. Assuming the use of a convolutional code with constraint length 7 and rate 1/2, the following shows the minimum required energy per bit to noise density ratios (Eb/NO) that can be tolerated to give a bit error probability of 10^{-5} for the various types of links encountered in the SDS architecture:

	Req'd E_B/N_o for 10^{-5} BER
1) LOS/Coherent Broadband Jamming	4.5 dB
2) LOS/Non-Coherent Multitone Jamming	10.0 dB
3) LOS/Scintillation Coherent Broadband Jamming	
No ISI Modes Diversity $B > B_C > R_B$	7.0 dB
ISI Large Diversity $B >> R_B \gtrless B_C$	7.0 dB
4) LOS/Scintillation Non-Coherent Broadband Jamming	10.0 dB

These ratios were used to determine link margins presented in Section VI.

C. TRENDS IN RADIATION HARDENED MICROELECTRONICS FOR SDI

TRENDS IN RADIATION HARDENED MICRO-ELECTRONICS

SUMMARY

The SDI program has defined two levels of radiation requirements, level 1 and level 2. Table A-1 presents the quantitative device parameters for these two levels.

The less severe application, level 1, is attainable with current technology and processing capabilities. Although there are not a lot of devices obtainable today meeting the level 1 requirements, the reason is market demand, not technology. With proper market demand, it is anticipated that the VLSI devices required to support SDI equipments could be obtained in CMOS, bi-polar, and GaAs, as needed by the specific application.

Level 2, on the other hand, has little chance of being implemented with presently manufacturable process technologies. An extension to existing technology and process cababilities will be needed. Two technologies appear promising for level 2 applications. These are:

> Gallium Arsenide (GaAs)- This technology is needed for applications requiring high speeds and medium gate densities. Processing has been demonstrated, producing low density devices with good total dose radiation hardness. The technology extension is needed to increase the gate densities, improve the transient radiation hardness, and address high volume production issues.
>
> CMOS-Silicon On Insulator (CMOS-SOI)- This technology is needed for high density, medium speed, and low power applications. Although MSI devices have been produced in a laboratory environment, technology work is needed to refine the process and to validate the anticipated inherent radiation hardness.

In summary, CMOS whether bulk or SOI will be the choice for level 1 complex processing applications, LSI, VLSI or greater. GaAs and bi-polar are applicable to level 1 equipments requiring very high speed, but possibly at the expense of power and density. The more stringent level 2 environments will necessitate the use of CMOS-SOI or GaAs. GaAs will be chosen in high speed applications and CMOS-SOI in medium speed, low power applications.

REQUIRED RADIATION TOLERANCE

The SDI Survivability, Acquisition and Tracking Program and the Radiation Hardened LSI Technology Program (SAT-8.1) have defined two survivability requirements, Levels 1 and 2, for SDI. Level 1 is applicable to ground based systems and space based demonstration models, while the more demanding Level 2 is applicable to space based systems. The requirements for the two levels are summarized in Table A-1.

Table A-1 Survivability Requirement Levels

	Level 1	Level 2
Total Dose (Rad(Si))	1.0 E__	3.0E__
Dose Rate (Rad(Si)/sec)		
Upset	1.0E__	1.0E__
Survival	1.0E__	1.0E__
Neutron (1MeV n/cm2)	1.0E__	1.0E__
Single Event Upset (Bit Errors/Bit-Day)	1.0E__	1.0E__
Directed Energy Weapons Upset to Protons (Bit Errors/Bit-Day)	__	__
Thermomechanical (cal/gm)	__	__

INTEGRATED CIRCUIT DEVICE TECHNOLOGY

The choice of process technologies to implement custom SDI integrated circuit requirements will be determined by two major considerations. The first is the general speed-power performance common to all spaceborne systems. The second is the severe radiation requirements under which SDI systems, in particular, will be required to function. The electronics of SDI systems are required to survive the prompt and delayed radiation from nuclear detonations, natural and nuclear-detonation-pumped charged particle belts, cosmic rays and directed energy weapons. Technologies which are currently in use or under consideration include:

- Silicon CMOS or Bipolar Devices
- Gallium Arsenide FET or Bipolar Devices
- Josephson Junction Devices
- Silicon on Insulator Systems (SOI)
- Silicon on Sapphire Devices (SOS)

Of the 5 technologies cited above, Silicon On Saphire and Josephson Junction are not believed to be viable candidates for the following reasons.

SOS is considered an obsolete process. Technical problems associated with the heteroepitaxial structure, while partially overcome, have continued to plague the technology.

In addition, the parasitic edge devices and back plane leakage path have severely compromised its radiation resistance, even for Level 1. Although heroic efforts have been mounted by some suppliers to overcome these inherent disadvantages, SOS appears to be a technology that has missed its window.

Josephson junctions, based upon superconducting materials, have lagged behind the Silicon and GaAs devices because of problems of implementing circuits at liquid helium temperatures. Although recent advances have produced working signal processing systems, currently this is not a mainstream technology, even for ground applications. This is, however, a rapidly changing area, which should be closely monitored for quantum breakthroughs.

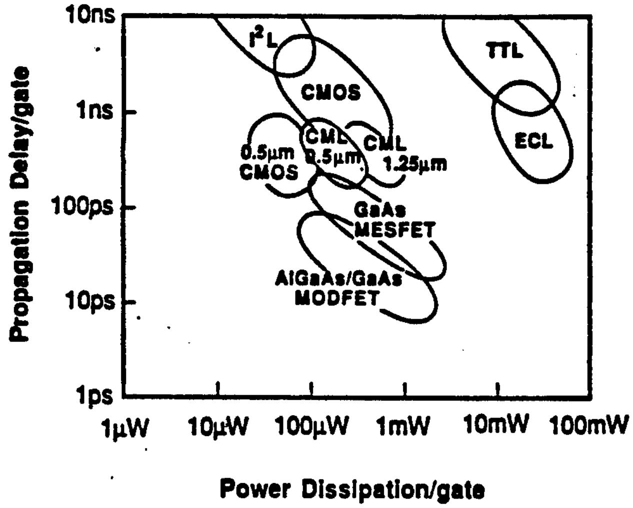
The remaining semiconductor technologies merit further consideration. Figure A-1 is a comparison of speed-power results for several advanced Si based and GaAs based IC technologies. The curves marked CML (1.25 microns) and CML (0.5 microns) represent results for VHSIC technology. All the results shown are for ring oscillators, thus giving a direct comparison on intrinsic gate speeds.

CURRENT CAPABILITIES

Recent process development efforts have increased the hardness of both Si and GaAs (Table A-2). Gallium arsenide MESFETS have been shown to be only minimally sensitive to a total dose of 250 Mrads (GaAs) and a neutron fluence of 1E14 neutrons/sq.cm. GaAs MOSFET circuits have shown no upset to dose rates of 1E10 rad/sec. Such radiation hardness levels are also representative of recently demonstrated Si capabilities. Radiation hardened CMOS (RHCMOS) circuits have been fabricated with demonstrated total dose hardness in excess of 1E7 rad, and latch-up and burn-out immunity to dose rates in excess of 1E12 Rad(Si)/sec. While current upset levels are of the order of 1-3E8 Rad/sec., current developmental goals in excess of 5E10 Rad(Si)/sec. are considered attainable.

It is not possible to say whether GaAs or Silicon is generically superior for Level 1 requirements. Applications must be examined on a case by case basis to determine which technology is most appropriate to a particular portion of a system. In general, when the highest possible speed is required, or when the lowest possible noise at high frequencies is required, gallium arsenide (even at higher cost/gate) will be the preferred choice. For large scale integration involving command and control functions, data processing, or low to intermediate frequency communication, where minimum power consumption is essential, silicon would be the optimum material.

Figure A-1 Comparison of Speed/Power For Various Technologies



Technology	Total Dose (Rad(Si))	Dose Rate Upset (Rad(Si)/sec)	Dose Rate Survival (Rad(Si)/sec)	NEUTRON (n/cm^2)	Comment
RHCMOS(2)	>1E7	1E11(4)	>1E12	>1E14	Projected dose rate capabilities. May satisfy both levels.
CMOS (Commercial)	>1E4	>1E8	>1E9	>1E14	Falls short in total dose.
CMOS SOS(3)	>1E6	>1E10(5)	>1E12	>1E14	Total dose problem. Not scalable below 3 micron.
CMOS (SOI)	TBD	1E12	1E12	TBD	Not mature, laboratory SEU/upset immune.
GaAs	>7E7	1E11(1)	>1E12	>1E14	High speed and dose rate, low power uses. Limited by high cost/gate, processing difficulties.

Comments:
(1) 5E10 demonstrated.
(2) Projected SEU capability of $1X10^{-10}$ errors/bit-day. RHCMOS is Radiation Hard CMOS.
(3) $2X10^{-9}$ errors/bit-day.
(4) 3E8 demonstrated.
(5) Only if hardened by design.

TABLE A-2 IC TECHNOLOGY HARDNESS

DISCUSSION OF HARDENING TO LEVEL 2 REQUIREMENTS-

The radiation requirements of Level 2 will only be attained through the implementation of a new technology base. The most likely silicon candidate at this time is the one that is known generically as Silicon on Insulator (SOI). (GaAs is a non-silicon candidate, and will be discussed later in this report.) While SOI systems lack sufficient maturity to consider implementation at this time, most of the component techniques required to assemble the process have been developed. In fact, some SSI/MSI implementations have been demonstrated. However, issues of manufacturability, sourceability, yield, and reliability have yet to be addressed. There remains a concern that SOI may have the same low total dose susceptibility as SOS. However, it is generally felt that an aggressive developmental effort in this area will most likely be successful.

To accelerate the development of RHCMOS and SOI technologies, radiation effects test structures and circuits will have to be developed and evaluated in the total dose, dose rate, neutron, and single event upset environments. GFE simulation facilities will have to be used for the evaluation of the susceptibility of the technologies to DEW SEU. All this presupposes the availability of a viable SOI process capability.

A comparison of radiation tolerance of Silicon Bipolar and GaAs circuits shows each can withstand total integrated dose and that both have difficulty withstanding transient radiation. Silicon Bipolar is hardenable to greater than 10 MegaRads by relatively common process modifications. GaAs circuits are inherently hard to total integrated dose. The semi-insulting GaAs substrate does not require the use of dielectric isolation such as Silicon Dioxide used in most silicon circuits. The omission of the dielectric removed the threshold variations and field inversion problems associated with charge storage in the oxides and the interface state generation problems encountered at the silicon-silicondioxide boundary. The resulting dielectric free devices suffer only minor performance degradation after greater than 100 MegaRads.

Transient upset manifests itself differently in Silicon and GaAs. The primary reasons for transient upset in silicon have to due with photocurrent generation and the effects the photocurrents have on power distribution (Rail Span Collapse) and circuits or individual transistors with gain (Secondary Photocurrent generation). Photocurrents are free charge formed by the radiation pulse that are collected in the depletion regions of junctions. Hardening of Silicon CMOS has been accomplished by replacing junctions used for horizontal device isolation with dielectric boundaries and vertical isolation to the substrate junction by SOI, a buried dielectric layer. Silicon Bipolar transistors are inherently PNP or NPN junctions and cannot be removed from the device structure. Transient hardening of Silicon Bipolar is therefore limited to minimization of photocurent

effects and will never achieve the exceedingly high transient radiation levels of Silicon CMOS and GaAs.

GaAs also has difficulty with transient upset. GaAs E/D circuits lack sufficient noise margin to tolerate the transient noise environment. Noise in the power distribution and a reduction in the insulating nature of the GaAs substrate, causing device to device condition combine to exceed the noise margin of the gates and result in upset. Current GaAs II E/D upset levels are

Figure A-1 Comparison Of Speed/Power For Various Technologies

similar to Silicon Bipolar (1E8 to 1E9 rads/sec), though improvement is rapid since the same efforts to improve circuit complexity are directly benefiting transient radiation tolerance. Heterojunction GaAs III FETs have noise margins many times better than E/D MESFETs and have demonstrated superior transient upset tolerance. Upset free work-through has been demonstrated at 5E10 Rads/sec.

COMPARISON OF SILICON AND GALLIUM ARSENIDE-

Silicon is an ideal material for the fabrication of VLSI circuits. Silicon can be easily purified; grows fused quartz as its native oxide to serve as a dielectric layer and diffusion barrier; is easily etched and mechanically strong; can withstand high processing temperatures; forms ohmic contacts to metallic conductors easily; and supports the formation of a wide range of active and passive devices such as NPN and PNP bipolar devices, N and P channel mosfets, JFETS, resistors, capacitors, etc. It is the ease of fabrication that causes silicon to be the dominant semiconductor technology in spite of its subordinate electrical characteristics.

Gallium Arsenide (GaAs), on the other hand, has nearly ideal dielectric properties at microwave communication frequencies. It has very high electron mobility so that extremely fast active devices can be fabricated. It has the flexibility of bandgap modification through the addition of ternary compounds to produce materials such as AlGaAs. Being a direct bandgap material, optically active devices such as LEDs and lasers can be integrated directly into custom configuration. Only the difficulties of circuit processing limit the utilization of GaAs for LSI fabrication.

Silicon Bulk CMOS will provide the high density radiation hardened process technology for all but Level 2 requirements where CMOS/SOI will be required. The high speed technology applications will utilize silicon bipolar in the near-term except for power critical and high transient dose rate environments. In the longer term both GaAs MESFET and GaAs heterojunction technologies will exceed both the performance and complexity achievable with silicon bipolar. Level 2 requirements will be met by GaAs Heterojunction technology.

CMOS technologies excel in complex processing and data storage

applications. CMOS's virtual lack of static power consumption makes it ideal for memories and complex digital processors where most internal nodes are static. Bulk CMOS also offers continued promise in radiation hardened applications. Total dose hardening efforts have resulted in hardened bulk CMOS devices that can withstand a MegaRad, with advanced processed offering 10 to 100 MegaRads of total integrated dose hardness, adequate in all applications. Transient hardening efforts have made progress by simply improving power supply distribution, enabling bulk CMOS devices to achieve in excess of 1E10 Rads/sec (Si). This level will improve still further without employing more difficult and exotic techniques such as Silicon On Insulator (SOI) technology.

SOI techniques are as yet unproven, having only been demonstrated at the MSI level in laboratory environments, but are expected to become producible in the next 5 years. Performance and hardening advantages may make SOI acceptance broad once manufacturable. The inclusion of the buried SiO2 layer reduces device capacitance, increasing speed or reducing power, while simultaneously eliminating the under-channel junction's charge collection volume. These improvements may result in both commercial and military application. CMOS/SOI is expected to tolerate 1E12 Rads/sec (Si) without transient upset. The buried isolation layer is also expected to provide Single Event Upset (SEU) hardness by interrupting the ionized charge funnel formed under the device along the particle track.

CMOS device speeds are improving with smaller geometries, though not sufficiently to offer an alternative to high speed Silicon Bipolar or GaAs. High speed applications will require the use of Silicon Bipolar or GaAs technologies. The choice of GaAs or Bipolar must be based on specific system requirements. Both are capable of speeds greater than 1 GigaHertz, with GaAs circuits operating as high as several GigaHertz.

Circuit complexity achievable currently with Silicon bipolar is approaching 10,000 equivalent gates (45,000 transistors). Silicon bipolar has made significant density strides in recent years utilizing self alignment techniques, buried contacts and more highly concentric device structures. Continued density improvement will continue tracking photolithography progress. Bipolar speeds have progressed due to the much smaller geometries, pushing device Ft above 10 GHz as high as 17 GHz. Gate delays of less than 100 picoSeconds have been demonstrated at gate powers of 4 to 8 milliwatts. Current Silicon Bipolar devices may be limited by total power dissipation in applications where such exotic cooling techniques such as liquid cooling are impractical. Flight applications will be required to limit total device complexity to remain when the bounds of conduction and radiated cooling capacities. Ground based applications are more flexible, currently accepting chip power dissipations as high as 30 watts.

Gallium Arsenide digital circuits have developed more slowly than Silicon. Original all depletion mode (GaAs 1) circuits met with

limited acceptance due to high power and low levels of integration. SSI to MSI level device complexity limitations, due to high power dissipation, resulted in minimal system speed improvement, utilized only in strategic circuit bottlenecks.

The introduction of Enhancement/Depletion (E/D GaAs II) mode circuits allowed significantly higher levels of integration due to reduced power consumption. GaAs II E/D circuit processing is today offering a relatively mature technology. Circuit densities in the LSI level, greater than 3000 gates, are currently achievable. Maximum integration levels are still limited by processing difficulties, primarily a lack of adequate noise margin to absorb process and parametric variations. GaAs II E/D does offer a speed-power product 3 to 5 times better than Silicon Bipolar. A current comparison of achievable density gives Silicon Bipolar a 3X to 4X greater complexity, but if each technology is allowed to mature to where total power dissipation again becomes the limiting factor in device complexity, GaAs circuits will achieve a higher level of complexity due to lower speed-power product.

Heterojuntion GaAs III circuits are currently progressing from laboratory to a manufacturable technology. GaAs Heterojunction Bipolar Junction Transistors (HBT) and heterojunction FETs are being developed. Similar to silicon, the HBTs are expected to find application in linear, analog and high speed applications. The FETs will operate at the lower power levels amenable to high density applications. Heterojunction GaAs FETs gates operating at 50 to 70 picoSeconds have been demonstrated at the 2000 gate level. This technology lags GaAs II MESFETs by several years but offers a speed-power product low enough to carry multi-GigaHertz GaAs ICs into the VLSI integration levels (10,000 to 100,000 gates) before being power dissipation limited.

In summary, CMOS whether bulk or SOI will be the choice for complex processing applications, LSI, VLSI or greater. Bulk CMOS will meet most radiation hardening requirements through 5E10 Rads/sec. More stringent environments will necessitate the use of CMOS/SOI. High speed applications will require Silicon Bipolar or Gallium Arsenide. Ultimately GaAs will exceed the density and performance of Silicon Bipolar but not for 3 to 5 years. In the interim, GaAs will only be chosen in power critical applications or due to high transient dose rate requirements. Level 2 environments will required the utilization of GaAs III Heterojunction technology. The maturity, manufacturability/cost, and recent advancements of Silicon Bipolar will preserve its hold on the high speed technology market share.

DISCUSSION OF VHSIC PROGRAM

The present effort of military IC technology is the VHSIC program, which has developed 38 very high speed integrated circuits using a 1.25 micron feature. This program also involves inserting these chips into nine brassboards. Currently all the chips have reached the testing phase and many have or are being

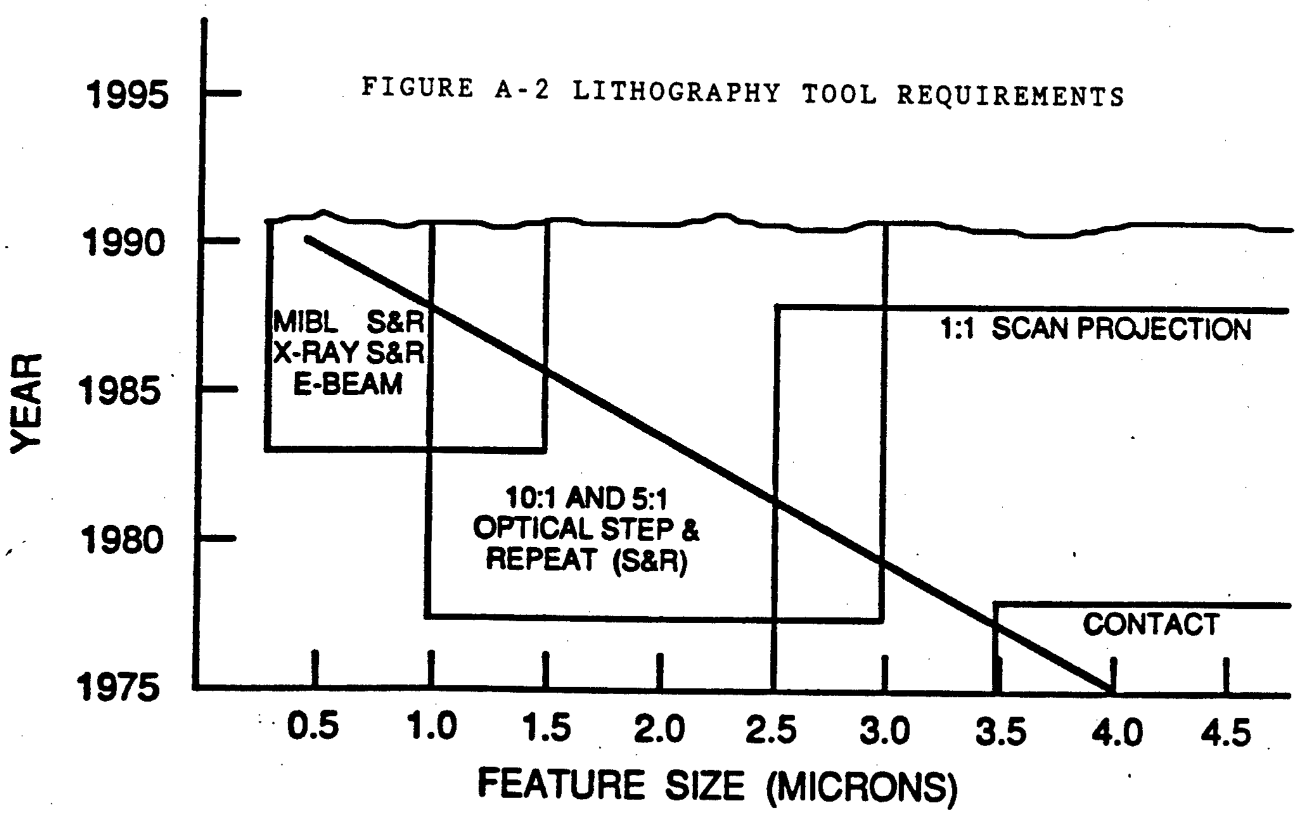
employed in the VHSIC brassboards. Furthermore, the yield improvement phase has been in progress for a year or more. Efforts are now being concentrated on the development and generation of the submicron (0.5 micron) chip technology.

Also, the current maturity of the gallium arsenide technology was evaluated. Presently this technology appears to be a viable option to silicon technology for high speed and radiation hardened applications.

VHSIC LITHOGRAPHY

The present high level of chip integration has resulted from the generation of micropatterns produced by the refinement of conventional optical lithography. The sophistication, reliability, and economic feasibility of electronic systems have increased in direct proportion to the increase in circuit densities of integrated circuit chips. Much of the performance enhancement of integrated circuits can be attributed to the increased circuit density and speed obtained by reductions in the feature size of circuit patterns. Figure A-2 is a forecast of pattern application line widths which must be supported by lithography tools, if the goals of the VHSIC program are to be met.

FIGURE A-2 LITHOGRAPHY TOOL REQUIREMENTS



The VHSIC Phase I chip prototyping and yield enhancement efforts established that optical stepper lithography can be employed as a 1.25 micron baseline technology. It also demonstrated that a hybrid "mix and match" patterning approach using both optical and E-beam lithography can be employed for the alignment of chips with 0.5 micron feature. The use of commercial projection aligners and optical steppers have proven to be feasible for the task of patterning super chips.

The fabrication of the VHSIC Phase II chip is a difficult task, since the complexities of this chip are anticipated to range from 1E5 to 2E6 gates per sq cm and chip sizes ranging from 0.7 cm to 5.0 cm on a side. Not only is prototyping an issue, but also future chip production line availability and operating costs are critical and unavoidable issues. Hence it can be concluded that micropattern generation of the submicron feature chips will require employment of E-beam, X-ray and Masked Ion Beam (MIB) technologies as well as optical lithography.

Basically, the VHSIC EBL prototype throughput requirements specify at least 20 (100 mm dia.) wafers per hour at a resist sensitivity of 20 uC/sq cm and a pattern complexity described as 1E6 geometries per sq cm, or a 30% wafer coverage.

Due to current business conditions and program withdrawals, the only VHSIC supported development that remains available for VHSIC Phase II chip prototyping and early chip production is the PE AEBLE-150. This machine offers a quick turnaround and customization of chips even below 0.5 micron in small quantities (less than 10,000) in a cost effective manner.

Due to its serial mode of information processing, EBL patterning will be expensive and impractical for large volume production. Because certain wavelength X-rays are inherently capable of being used for submicron patterning and parallel data transfer, the VHSIC program includes the development of an X-ray step and repeat system (XSR). The VHSIC XSR development is well along in development (Perkin-Elmar).

ADDITIONAL DEVICE SPEED-POWER INFORMATION

The gate power-delay product is the most used figure of merit when evaluating the performance of an integrated circuit gate. By definition it is:

$$U_g = p * t_g \qquad (1)$$

where U_g = energy in joules.
p = gate dissipation in watts.
t_g = gate delay time in seconds.

Equation 1 represents the minimum energy dissipated in a switching circuit when it changes from one binary state to the

alternate binary state. This energy manifests itself as heat and as such it places an upper bound on the overall operation of the integrated circuit from a power dissipation consideration. For example, if we assume that chip contains N gates having a gate power-delay product, Ug, and an average gate clocking frequency Fc, then the power dissipation of the chip is given by:

$$Pc \geq 2N*Fc*Ug \qquad (2)$$

where Pc = Power dissipation capability of chip in watts.
N = Number of gates on the chip.
Ug = Gate power-delay product expressed in joules.
Fc = Average gate clocking frequency.

Thus it can be seen that ultimately the performance of a chip is a direct function of the ability to dissipate the heat it generates. For the purposes of this investigation, we will assume a permissible heat dissipation is two watts. This dissipation is commensurate with the nominal values of the VHSIC Phase I chips.

Table A-3 shows the maximum values of the gate delay-power products that are consistent with maintaining a 2-watt chip dissipation for chip levels of integration ranging from the device level through 100,000 gates and for average gate clocking frequencies of 0.1 MHz to 10 GHz.

Inspection of this table reveals that very high speed, very large scale integrated circuits imposes extreme demands for low delay-power products because of the high average clocking frequencies and the large number of gates on the chip. For example if $N = 10^4$ and $F_c = 1$ GHz, then the delay-power product of the gate technology must be less than 0.1 joules. Even allowing for the fact that the power dissipation for larger chips could safely be much greater than the 2 watts (assumed in Table A-3), power-delay products less than 1 picojoule are essential if very high speed VLSI is to be a reality.

At high levels of circuit integration (> 10,000 gates), the interconnect energy loss is also a significant factor. It has been shown in the technical literature that as the chip integration levels increase above 20K gate complexity the single gate performance is deteriorated by the interconnect wire of the gates within a chip, then the performance of the chip is essentially independent of the individual gate performance. Detailed information concerning this phenomena is located in References 1 and 2.

A potentially powerful method for increasing switching speed is to replace the silicon technology with another semiconductor technology (such as Gallium Arsenide) having superior electronic properties. Gallium Arsenide technology provides a factor of five improvement because of its inherent electron mobility factor and the advantage of the insulating substrate.

Figure A-3 is a graph of the power-delay product as functions of the gate delay and gate power dissipations for most of the silicon circuit technologies and also that anticipated with the gallium arsenide technology.

For any given point on the graph, the ordinates axis defines the gate delay in nanoseconds, the x axis defines the respective gate dissipation in milliwatts, and the intersecting diagonal line provides the magnitude of the power-delay product in picojoules.

Hence, it can be noted that the diagonal lines of the graph toward the lower left-hand corner of the graph represent smaller power-delay products. The solid triangles represent lower power-delay products achieved by the VHSIC Phase I circuit technologies (all implemented with the silicon technology) and, as such, provide a benchmark of the current military integrated circuit technology.

Referring to Figure A-4, it can be observed that CMOS/SOS circuit technology and gallium arsenide technology exhibit the lower power-delay products, and it is somewhat less than 0.1 picojoule. CMOS/SOS possesses the minimum gate power, while gallium arsenide technology has a small gate delay, about 40 times less than CMOS/SOS. However, the gate power dissipation of the gallium arsenide gate is approximately 60 times that of CMOS/SOS. Therefore, in applications where very large scale integration is required and speed is not a limiting factor then the CMOS/SOS is an optimum choice. Applications where speed is the prime requirement, gallium arsenide technology is the most optimum selection and as such, the chip level is limited by its gate dissipation. See References 1, 4 and 5 for additional details.

VHSIC DENSITIES-

A valuable benchmark for accessing the military silicon integrated technology is the results obtained on the VHSIC Phase I effort. The contractors of the VHSIC Phase I utilized five circuit technologies, NMOS, ISL, CMOS, STL and 3D Bipolar. These chips were developed using a 1.0 to 1.25 micron feature size. Table A-4 provides a summarized tabulation of the chip parameters, the chip size, gates per chip, device count per chip, gate dissipation, gate delay and the power-delay product.

In summary it can be seen that the current nominal chips are 0.119 inches^2 (0.34 x 0.35), and the gate densities for this chip size range from 131,000 to 364,000 gates per inch^2 with the largest densities achieved by the NMOS technology. The power-delay product ranges from .1 picojoules (CMOS) to 3 picojoules (3D bipolar).

During the past five years, considerable attention and effort has been devoted by the IC industry to the development of digital integrated circuit area using the gallium arsenide technology. Table A-4 b summarizes the chip performance that is achievable in the laboratory today and a projection of what should be

achievable in five years.

It can be observed from this table that the key features of this technology are the power-delay product, the very short gate delay, and its excellent radiation performance. The level of chip integration is somewhat less than that achievable with silicon technology. One of the key issues that remains to be resolved is the degradation of the chip performance when the chip level of integration attains a 10,000 gate (and greater) complexity. At these levels the chip performance is more dependent upon the interconnect effects rather than the individual gate performance.

	Clock Frequency					
Gates/Chip	0.1 MHz	1.0 MHz	10 MHz	100 MHz	1 GHz	10 GHz
ULSI 1E5	100 pj	10 pj	1 pj	0.1 pj	0.01 pj	0.001 pj
VLSI 1E4	10^3 pj	100 pj	10 pj	1 pj	0.1 pj	0.01 pj
LSI 1E3	10^4 pj	10^3 pj	100 pj	10 pj	1 pj	0.1 pj
MSI 1E2	10^5 pj	10^4 pj	10^3 pj	100 pj	10 pj	1 pj

Table A-3 Maximum Gate Dynamic Switching Energies for Various Average Clock Frequencies (2-Watt Chip Dissipation)

When the GaAs technology is implemented into logic chips, there are several key issues which must be considered. The GaAs circuitry requires interface circuitry when the internal chip functions are connected to circuits in another chip. Therefore, the logic output signals are implemented with driver circuits. Each driver circuit consumes 15 to 30 milliwatts, so that the total driver power consumption is approximately 100 to 250 times that of a single Ga As logic element. One can conclude that the chip interface circuitry is not a trivial concern. Furthermore, the real estate occupied by this driver circuit is large in comparison to the GaAs logic cell real estate. One approach being considered is the application of optical coupling for chip to chip signal interconnects.

TABLE A-4a VHSIC Phase I Chip Parameters

Circuit Technology	Chip Size (sq. in.)	Gate Count (K)	K Gates Per Sq. In.	Gate Diss (mW)	Gate Delay (nanosec)	Power Delay Product (pJ)
3D	0.314 x 0.272	11.8	138	0.38	7.9	3
STL	0.35 x 0.35	16	131	0.15	7.4	1.1
ISL	0.3 x 0.3	27.3	303	0.07	10.0	0.72
NMOS	0.32 x 0.32	37.3	364	0.089	8.0	0.7
CMOS (Hughes)	0.368 x 0.315	18	154	0.04	5.0	0.2
CMOS (West.)	0.34 x 0.35	23	192	0.016	6.0	0.11

Table A-4 b Gallium Arsenide Chip Parameters

Parameter	1986	1991
Feature size (uM)	1.0	0.5 to 0.7
Gate Power (mW)	.5	.5
Gate Delay (ps)	100	70
Power-Delay (pJ)	.05	.035
Integration Level (number of gates)	4000	15000 to 20000
Radiation		
Total Dose Rad(Si)	$10^7 - 10^8$	10^8
Transient Rad(Si)/sec	$10^9 - 10^{10}$	$10^{11} - 10^{12}$

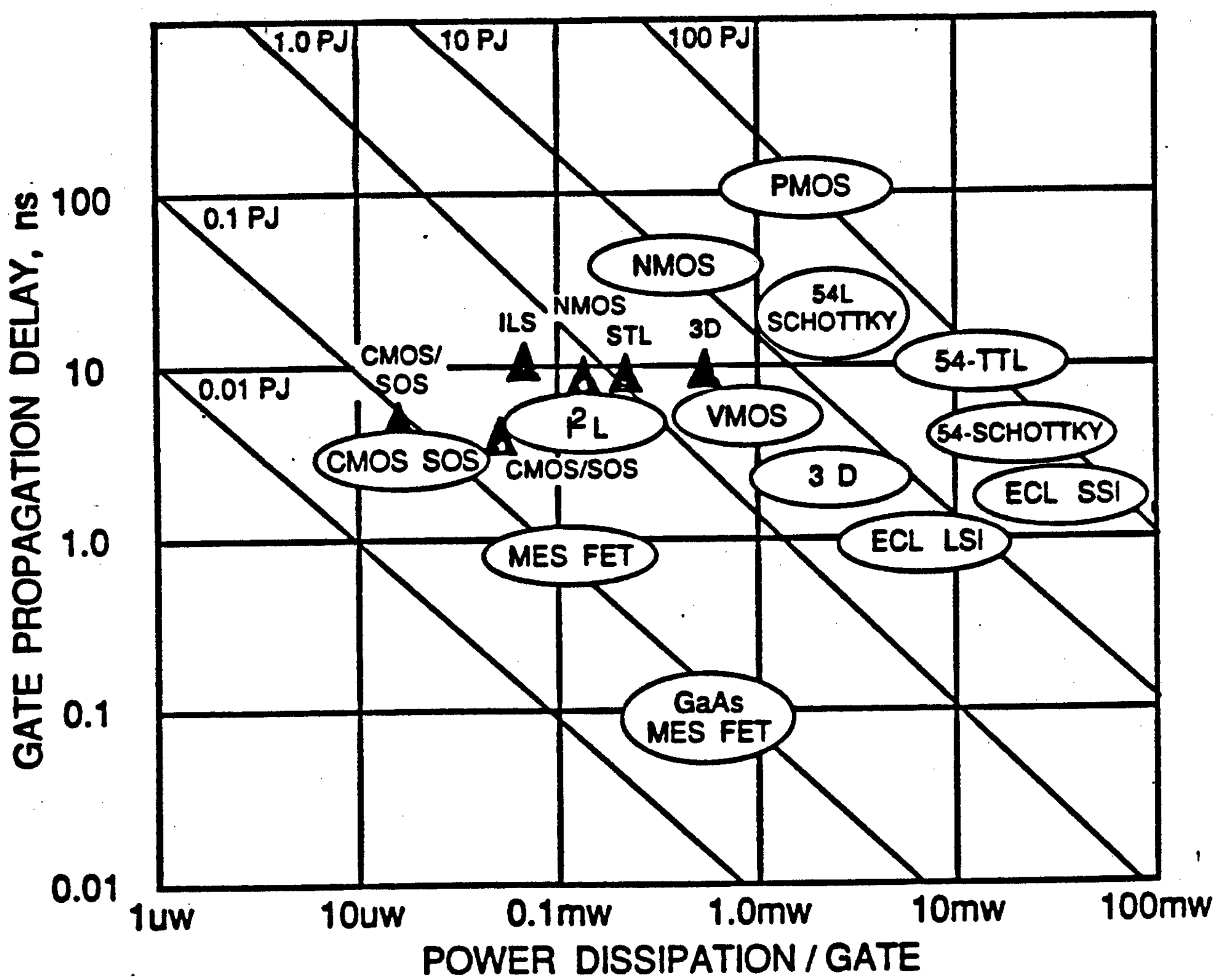


FIGURE A-3 SILICON AND GALLIUM ARSENIDE GATE CHARACTERISTICS

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D. EMBEDDED COMSEC FOR SDI

SUMMARY-

COMSEC imbedment is a loosely defined term. The basic concept is to "imbed" the COMSEC function into the system as an integral part of the system. How this is accomplished is still subject to debate. Depending on the source of information, COMSEC imbedment ranges from a chip or chip set which is added to the system components, to an intelligent standalone data processing equipment which requires minimum inputs and provides few outputs. The compromise of these two extremes is a medium size module which has a small amount of "intelligence", thus requiring less external control than a chip set but more than a standalone equipment.

This white paper discusses COMSEC Embedment at each of the three levels, chip(s), module, and a standalone unit. In principle, the advantages of embedded COMSEC is a reduction in overall system size, weight, power, and complexity resulting from sharing resources (such as housings, power converters, system controllers, etc.) between the COMSEC function and host equipment function. In summary:

> Chip embedment usually results in the simplest system, but may cause undue administrative problems, and a considerable increase in non-recurring cost and program risk.
>
> Module embedment may result in a slight increase in host equipment complexity (over chip embedment), but provides a tremendous reduction in the administrative costs and risks.
>
> The standalone COMSEC approach is perhaps the highest recurring cost approach, but presents a lesser non-recurring cost and risk situation.

Many factors must be considered when determining the level of COMSEC embedment. The following discusses some of these factors.

SECURITY AND ADMINISTRATIVE FACTORS-

For the chip and module embedment case, the host equipment supplier is obligated to implement many security features (such as the alarm test, red-black separation, SFA analysis, etc) which are perhaps totally foreign to him. Some host equipment suppliers may not even have a secure facility and personal clearances.

For the chip case, the host equipment would be responsible for the TEMPEST design, analysis, and subsequent verification testing. For the module case, some of the TEMPEST design would be included in the module, but the host equipment developer is still responsible for the physical isolation and power supply aspects of TEMPEST, and for performing the system TEMPEST testing .Again. this may be a totally new discipline for him.

For the chip and module embebment cases, the host system is responsible for implementing the local agent portion of the

network re-key protocols. The whole concept of rekeying may be foreign to the host equipment supplier.

The procuring agency would be obligated to provide "applications information" as part of the host equipment specifications. In addition to the normal KG requirements specifications (including such things as the communications protocols, variable processing, chip interfaces, randomization, alarm test, etc.), additional tutorial and philosophy/doctrine information would probably be needed. The degree of support from government security agencies (monitoring the design, attending design reviews, etc.) would probably be increased, so that problems could be detected and corrected before the design is frozen.

Most likely, chips and modules would be procured from one or more traditional COMSEC equipment suppliers, so the procuring agency would probably do the vendor control and monitoring in the normal manner. There are probably numerous different suppliers of host equipment into which the COMSEC function is embedded. The COMSEC procuring agency must monitor each one of them, including providing security guidelines, monitoring the design, reviewing and approving the analyses, attending design reviews, etc.

Although the chip embeddment may result in the minimum hardware system implementation, the approach imposes an administrative burden on the host equipment supplier and the procuring agency. This approach may be practical in situations where the host-system supplier is also cognizent of cryptographic issues, has a cleared facility, is up to speed on security issues, understands protocol issues with key management, and understands TEMPEST design and testing. It does not seem practical, however, in situations where the host equipment supplier has never been exposed to COMSEC issues.

The standalone COMSEC approach is the simplest from an administrative standpoint, and probably results in the lowest non-recurring cost, least program risk, highest security, but the highest recurring cost.

Chip embedment appears to be the least desireable, since it places the maximum security responsibility on the largest number (and possibly least experienced) equipment designers, and distributes the security responsibility widely.

The embedded module case appears to be a reasonable compromise between non-recurring cost and administrative risks. The COMSEC design, security analyses, etc. are confined to one vendor (the module supplier). Although the host equipment supplier still must maintain some security responsibility (TEMPEST, and some functional control) his involvement is considerably less than in the chip case.

The extreme case is the standalone COMSEC case, where security responsibility is clearly maintained with a single vendor, the COMSEC equipment supplier. The COMSEC is largely transparent to

the host equipment being protected.

CONTROL COMPLEXITY-

The next factor to consider is the embedment impact on system complexity and processing capabilities. If a chip set is to be integrated into a system assembly, the processing power to maintain that chip set and to perform general housekeeping functions must be added to the system.

The next higher level of embedment would involve a module which would handle the general housekeeping functions of the chip set and require a lesser degree of control from the host processor during traffic operations. The module approach decreases the amount of processing which must be dedicated to the COMSEC function, when compared to the chip approach.

System processing power requirements are reduced even further if the stand alone data processing approach is taken. This approach requires only rudimentary control functions from the host system processor. The COMSEC system would perform its own checks and control all COMSEC housekeeping functions. It could be designed to perform self diagnostics and provide status indications.

The most important thing to keep in mind is the complexity of the function which the COMSEC equipment must perform. This complexity will directly affect the next factor, the system interconnections.

SYSTEM INTERCONNECTIONS-

The chip or chip set would require a large number of interconnections. All diagnostic signals, SFA critical signals, and traffic processing signals must be accessed. Most likely, the chip would be designed to mount directly on a printed circuit board or in a socket. Hopefully, the chip packaging would be compatible with the host equipment supplier's board assembly procedures, so special handling would not be required during board assembly.

The module approach would probably require a cable harness or back plane connection to connect it into the host system. It would also require area or a platform for mechanical mounting into the host system. The number of physical interconnects required would vary depending upon the extent of the module local intelligence. The more intelligence the module contains, the fewer the number of interconnects which would be required.

The standalone equipment would require minimal interconnection between the system and the COMSEC equipment. However, this approach would require the largest area on the platform.

POWER CONSIDERATIONS-

A tradeoff of power is also an important factor to consider

between the three approaches. The chip set is the most efficient, because it would operate from power on the host system printed circuit board. Assuming chip voltage levels were compatible with the host system, no extra power converter or regulators would be needed (except possibly for TEMPEST). Additionally, sharing resources with the host system (such as using the host controller for the KG function) probably requires less power than adding an additional control function.

The module could be designed to operate from the prime power, or from a regulated or semi-regulated power bus. The better regulated the power bus, the more efficient the module could be by eliminating the need for internal regulators.

The standalone equipment could also be powered by a regulated or semi-regulated power bus. The total power required by this approach is probably greater than the other two approaches, since it requires the most circuitry.

SPECIFICATION AND INTEGRATION ISSUES-

Before beginning a discussion of the specification, integration, and testing of COMSEC embedment approaches some other considerations should be presented. When considering which embedment approach to use great care must be exercised not to apply one method indiscriminatly. It is not appropriate to assume that one approach is best for all application. In a low speed, simple application the chip approach may be the best. However, the chip approach could be very cumbersome when applied to a high speed or complex function. Simply put, all aspects of an embedment approach should be considered when trying to choose the one best suited.

COMSEC embedment tends to work best if standardization could be achieved. Simple requirements such as power supply voltages and regulation specifications, standard packages and mountings, standardized connectors, standard signal voltage levels and timing characteristics. This standardization may lead to inherent inefficiency in an embedment system. The amount of inefficiency is completely dependent on the versatility of the COMSEC embedment component. This versatility will be a direct result of the design specifications of the embedment component.

When a COMSEC element has been identified for embedment, the next task is to determine which embedment approach will be choosen. After the approach is choosen the task of determining the specifications can begin.

If a chip implementation has been choosen, a large amount of specifications will be required. The mechanical outline, heat sinking techniques available, temperature design limits; input and output data and clock timing relationships and amplitudes, leakage currents, frequency of operation, power supply voltages and functional task. The best scenerio for the specification of any approach is a dialogue between the system integrator and the

COMSEC supplier. The greater the level of interconnect complexity the more critical the definition of the COMSEC equipment task becomes.

The earlier the specification can be given to the host the better the chance for a useful piece of equipment. The ideal time to provide the detailed information on actual device operation is after the part has been fully tested. Because this is usually too late in the program a compromise must be struck. The best place to compromise seems to be about the time the part has been pronounced operational but before it has been fully qualified. This would yield preliminary data which can be used by the system designer to firm up system design contigent of some risk.

Module specifications should contain much the same information as chip specifications. The module specification will probably contain fewer input and output specifications because of the greater integration within the module. The specification should still contain information on temperature limits, power supply characteristics, operational frequency and the functional task.

The stand alone COMSEC equipment would probably have even fewer input and outputs than either the module or the chip. The type of information necessary for the stand alone specification would be the same as the information required for the module approach.

The specification of the TEMPEST requirements for the chip and the module approach would be different. Traditionally TEMPEST has been a consideration for the COMSEC equipment supplier. The chip and module approach move some of this responsibility to the system integrator. These two approaches also complicate the system integrator security fault analysis task. The integrator must now consider the consquences of compromise via more interfaces.

Theoretically the test of COMSEC embedable elements would not be difficult if all components of the system met original specifications. Practically it would be safe to assume that problems will be encountered and a supplier representative may need to be accessible during system integration if not present to assist. Problems worked through a resident liason intimately familiar with the comsec equipment could reduce problems and save time.

The testing of the chip, module or stand alone equipment would be performed by the COMSEC supplier to assure that the piece meets all specifications. The piece would then be delivered for integration into the system.

COMSEC embedment is a comlex issue with merits and drawbacks. Some system components will lend themselves easily to embedment and others will not. Forcing embedment on all parts of the system would not be wise without considering all of the aspects involved. The nature of embedment also leads to a need for increased dialogue between system and COMSEC companies.

E. IMPACT OF COMPUSEC ON FAULT TOLERANT COMPUTERS

A. Introduction And Summary

Trusted application software is still perceived to be a major SDI risk area, requiring quantum improvement in software generation and validation techniques, including tools. In general, the concern extends well beyond multilevel data security protection. Security compromises due to software errors are disasterous, but blowing up Philadelphia due to a software error is generally considered to be a no-no.

Many of the concepts called out in the orange book (in the context of MLS) are applicable to provably correct software in other applications. This includes such things as a formal (mathmatically rigorous) policy statement, partitioning the software into a trusted set and untrusted set, formal specifications, formal analysis and verification, configuration control, etc.

This paper is a first cut at identifying areas of interaction between fault tolerant processors and COMPUSEC. For the sake of this discussion, COMPUSEC is not confined to a strict MLS context, and is considered to include all trusted applications software.

In summary, there seems to be compatibility between the fault tolerant processor architecture and COMPUSEC. One possible problem is in the area of run-time testing, where test features would be required to tamper with the security mechanisms. The real divergence is between the applications software and COMPUSEC, primarily from a performance penalty. Details are presented in the following sections of this white paper.

B. Current Situation With Traditional MLS COMPUSEC-

1. Orange Book is well established and widely distributed.

2. A1 certification has been obtained for at least the SCOMP. It can be done!

3. The Trusted Network Interpretation of the orange book is still in formulative stage, and is apparently controversial. It is this adaptation that is probably applicable to the BM/C3 processing.

4. NSA certification still appears to be very Ad Hoc and open ended. It is not clear how to scope and propose a program requiring COMPUSEC, nor how to maintain schedules during the conduct of the program.

   o open ended- impossible to budget and schedule. You're done when NSA says you're done. Hardware and software fixes may be demanded at any point in the program.

   o Lots of extra meetings, reports, travel, etc.

o Hard to find qualified people to do it- Its a rotten job, and new enough that there are not a lot of people who have done it before.

5. Some tools available, lots more needed. Many of the existing tools need upgrading.

6. No known tool to go from problem specification to object code

C. Areas Of Compatibility Between COMPUSEC And Fault Tolerance.

1. Fault Tolerance, particularly where hardware fault masking is needed, provides good assurance that the processor hardware contains no undetected failures. This assurance is provided essentially continuously, without the overhead of real time test and diagnostic routines. Although the Orange book pre-supposes that the hardware is perfect, the fault tolerance via fault masking provides high assurance that the hardware actually meets these constraints.

2. Fault tolerance and robust software design needs the support of strong memory management, privileged instructions affecting system state and/or configuration, memory integrity (no undetected random errors), address bounds checking, run-time error trapping (such as overflow and underflow, data tag violations, capability violations, etc) and task partitioning. These attributes are also important to COMPUSEC.

   Data abstraction is also beneficial to both. If a process references data by a logical rather than a physical name,the hardware can more easily substitute a new physical storage element to hold the object in case the original storage element fails. Error correcting codes may be used to protect the data integrity during the storage failure.

   A processor chosen to support a fault tolerant application must have these inherent attributes as a starting point. COMPUSEC requires them as a starting point, also.

D. Areas Of Conflict With Respect To Processor Architecture.

1. Fault tolerance requires thorough built in testing, probably including special hardware which might defeat some of the security mechanisms. (Examples: Control logic to provide direct access to "hidden" registers, provisions to dump the contents of the cache, provisions for forcing violations to occur, maintaining memory access restrictions while testing the memory management hardware, etc.). This is a significant conflict.

2. Addition of alarm test circuits for COMSEC processors could be a problem. This feature requires providing both hardware and code

to deliberately force security violations (presumably, under a controlled and benign environment) to insure that the logic can detect them. This circuitry provides a attack point for denial of service, and increases the system failure rate, both due to extra program memory and extra hardware logic. This is a significant conflict.

3. Fault tolerance starts with maximizing inherent equipment reliability. Adding hardware features to support COMPUSEC (such as hardware security label enforcement, tagged registers, tagged memory, capability-based addressing, etc.) decreases reliability. Additional memory required (separate instantiations of the software, extra code for added features, buffers for audit data collection, etc.) increases the memory unreliability. A significant factor in the memory area, but probably not as significant in the remaining hardware areas.

E. Areas of Conflict With Respect to the Application.

1. In general, COMPUSEC, through its formal isolation between functions, strict control of information flow, etc. reduces throughput significantly. In a situation where performance is already critically taxing the hardware state of the art, this is a major problem.

2. Audit Data collection eats up memory, processing time, and communications bandwidth. All of these are precious resources.

3. The application will probably require multiple processors, and some form of distributed operating system. This could be a critical design problem in a COMPUSEC environment. COMPUSEC wants everything to be very deterministic and analyzable at the design phase. It discourages run-time decisions, task repartitioning based on current processor loads, run-time hardware or software reconfigurationing, etc.

F. Policy Questions-

1. Use of Cache Memory.

Cache memory is frequently used in high performance processors to minimize bus contention and to provide fast access to data and instructions. From a COMPUSEC standpoint, an issue to consider is the requirement for object reuse.

It is possible that the data Cache could contain sensitive information after a context switch from a trusted process to an untrusted process. In addition, it is probably impractical to predict, model, and/or analyze what information might be in the Cache at any instant of time.

For maximum performance, it is undesirable to flush the Cache whenever a context switch is made, or when control is passed from a trusted process to an untrusted process. Since the Cache data

is not directly accessible by normal software means, it seems reasonable to assume that the Cache need not be subjected to object reuse restrictions.

2. Audit Data Collection and Archiving.

Another policy point to consider is the importance of collecting and maintaining auditing data during the periods of high peak loading (such as the start of battle). It may be desireable to back off on the data collection, so that memory can be preserved for more important functions (such as track files), so that link overhead to distribute the information can be preserved, and to reduce the processor loading.

Also, it may be desireable to flush the collected audit trail when re-configuring in response to a hard failure. The savings are in a smaller data base which must be preserved in response to a fault.

3. Mass Storage And RAM-Based Software.

In all likelihood, the majority of the applications software will be executed from RAM, with only a small subset (probably not even all of the TCB) contained in RAM. Reasons for this are:

- o To support fault recovery, resources must be obtained from a "spares pool". It is unlikely that a spare could contain enough ROMs to cover all possible assignments.

- o The two mission concept, the tasks changing as a function of orbit, and the hierarchical node functional redundancy probably require that very different software be executed as a function of time. Minimizing hardware complexity will preclude having all software resident, with overlaying occuring to configure the program for the current mission phase.

- o With the long life expectancy, concurrent ground simulation and testing, and complexity of the overall software, changes and fixes are inevitable.

Again, it is possible that security software and trusted software will be involved in the remote loading operations. The fault tolerance must be adequate to mask the effect of RAM bit errors, so that should not be an issue. The real issues involve a trusted path between the ground station and the mass storage device, and a method for authenticating and validating the program loading, and guaranteeing a secure initial state. Has the security center dealt with this issue before?